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Validation of the Hot Strip Mill Model

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J. Description/Abstract
The Hot Strip Mill Model (HSMM) is an off-line PC based software model originally developed by the University of British Columbia (UBC) and the National Institute of Standards and Technology (NIST) under the AISI/DOE Advanced Process Control Program. The HSMM was developed to predict the temperatures, deformations, microstructure evolution and mechanical properties of steel strip or plate rolled in a hot mill. INTEG process group undertook the current task of enhancing and validating the technology. With the support of 5 North American steel producers, INTEG process group tested and validated the model using actual operating data from the steel plants and enhanced the model to improve prediction results.

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AISI/DOE Technology Roadmap Program

Final Report

0040 - VALIDATION OF THE HOT STRIP MILL MODEL

by

Richard A. Shulkosky
David L. Rosburg
Jerrid D. Chapman

March 30, 2005

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No. DE-FC36-97ID13554

Prepared for
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Prepared by
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Pittsburgh, PA 15220

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Report Documentation Page

Title and Subtitle:

Validation of the Hot Strip Mill Model

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Abstract:

The Hot Strip Mill Model (HSMM) is an off-line PC based software model originally developed by the University of British Columbia (UBC) and the National Institute of Standards and Technology (NIST) under the AISI/DOE Advanced Process Control Program from 1993 – 1998. The HSMM was developed to predict the temperatures, deformations, microstructure evolution, and mechanical properties of steel strip or plate rolled in a hot mill. In 2001, INTEG process group, inc. undertook the current task of enhancing and validating the technology developed by the UBC. With the support of the AISI, DOE and five North American steel companies, INTEG embarked upon a multi-year plan under a DOE TRP project to upgrade, enhance and validate the model referred to as the AISI Hot Strip Mill Model (HSMM) version 4. The steel company participants (Dofasco, IPSCO, Stelco, US Steel, Weirton Steel) formed the HSMM Enhancement Group to provide input and support to the effort. The goals of this project were twofold: 1) test and validate the existing HSMM using operating data from the plants; and 2) enhance the HSMM as required to improve the results.

With the release of HSMM version 6.2, the goals of the project have been successfully completed. An extensive validation and verification program for the enhanced HSMM was performed using a multitude of samples from the Enhancement Group steel companies. Excellent agreement was obtained for tensile strength from a variety of steel chemistries and mill configurations. Enhancement features incorporated into versions 6.0, 6.1, and now the final version of the HSMM, 6.2, that have made it more flexible and practical to use include:

- Improved user interface
- Ability to link all models and track the material through the entire mill
- Improved temperature and force modeling
- Ability to calibrate the temperature and force models from plant data
- Ability to view and adjust the microstructure calculation algorithms and coefficients

The supporting steel companies have found outstanding value in the HSMM in saving them time and money for a variety of practical applications. The HSMM continues to be marketed and sold

on a global basis as the industry's leading PC-based off-line model for helping steel producers and researchers improve the hot rolling process.

FORWARD

INTEG process group, inc. would like to thank the American Iron and Steel Institute and the Department of Energy for their continued financial support over the past four years enabling the HSMM to be enhanced and validated so that it is a practical tool for the steel industry. The assistance and support received from Joe Vehec, Director of the AISI Technology Roadmap Program, over the years was very valuable and appreciated. Larry Kavanagh and the staff at the AISI in Washington, D.C. are also warmly thanked for their continued support throughout the project.

We would particularly like to acknowledge the efforts of Keith Barnes, Mark Fenton, Brian Joel, and Tibor Turi of Stelco; Brian Nelson and J.J. Fitzpatrick of Dofasco; Matt Merwin and Eugene Nikitenko of U.S. Steel; Cache Folkman, Shaojie Chen, and Steve Yocom of IPSCO; and Rich Frey of Weirton Steel (now part of ISG) for the invaluable input and leadership they have provided over the course of the four-year project. We are also grateful to all the HSMM Enhancement Group companies for providing operating data and for their constructive feedback.

We would like to recognize the strong technical contributions of UBC, in particular Dr. Matthias Militzer and Dr. Vladan Prodanovic for providing background information on the model, adding new models for a new dual-phase steel, as well as on-going enhancements for the ROT; the University of Pittsburgh, BAMPRI, in particular Dr. Anthony DeArdo and Dr. Isaac Garcia, for conducting an analysis on the model; and the consultants who supported various tasks in the development of the enhanced version including, Dr. Vladimir Ginzburg, Naum Kaplan, Robert Ballas, Steven Lechuk and Dr. Daqing Jin (the lead researcher for the original project now an employee of The Timken Company).

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EXECUTIVE SUMMARY

The Hot Strip Mill Model (HSMM) is an inventive off-line PC based software model originally developed by the University of British Columbia (UBC) and the National Institute of Standards and Technology (NIST) under the AISI/DOE Advanced Process Control Program from 1993 – 1998. The HSMM was developed to predict the temperatures, deformations, microstructure evolution, and mechanical properties of steel strip or plate rolled in a hot mill. In 2001, INTEG process group, inc. undertook the current task of enhancing and validating the technology developed by UBC. The objective was to test, upgrade and validate the core models used for predicting the temperature, forces, microstructure evolution and final mechanical properties of steel produced on a hot strip mill. The scope of work includes validating and/or replacing various sub-models, adding practical application functions, updating the users interface to facilitate the ease of use of the model and to provide adequate documentation

With the support of the AISI, DOE and five North American steel companies, INTEG embarked upon a multi-year plan under a DOE TRP project to upgrade, enhance and validate the model referred to as the AISI Hot Strip Mill Model (HSMM) version 4. The steel company participants (Dofasco, IPSCO, Stelco, US Steel, Weirton Steel) formed the HSMM Enhancement Group to provide input and support to the effort.

The project included a detailed review of each sub-module of the model and a validation and/or replacement of each sub-module. Practical application functions, an updated user's interface to facilitate the ease of use of the model and adequate documentation was to be provided. A five-phase plan was developed to validate the Hot Strip Mill Model. Phases 1, 2 and 3 of the extended work plan were to conduct a technical audit of the model and to develop a plan to improve the model for practical applications. Phases 4 and 5 were to develop, validate and calibrate an enhanced version of the model with proper documentation, advanced modules, etc.

Phase 1, which undertook several tasks to bring the HSMM to a certain level of usability, was completed during the 3rd Quarter of 2001. INTEG then released to the participants on August 4, 2001 an updated version of the HSMM.

Phase 2 was to flow chart, document and identify the inputs and outputs of each module (or sub module) for the current version of the HSMM. Although some areas of the model were difficult to document due to limited information, this phase was completed as much as practical during the 1st Quarter of 2002 and was to be completed during phases 4 and 5 when additional information was available.

Phase 3 was to validate each sub module, but validation of each sub module using alternate models or plant data was not possible due to the design of the original model. Instead, based upon previous tests and published results of the model by the steel companies and UBC, an evaluation of the modules as a whole was completed as much as practical during the 1st Quarter of 2002.

Phase 4 involved the integration of the existing and new modules to make a cohesive model capable of covering all the needed functions to properly predict the temperature evolution,

forces, microstructure evolution and final mechanical properties. This task was completed and validated with an initial set of data in the 4th Quarter of 2002.

Phase 5 involved the validation of the model and was completed in the 4th Quarter of 2003. Excellent agreement was obtained between the actual and calculated values for tensile strength and yield strength. Additional work under Phase 5 was completed in the 1st Quarter of 2004 and resulted in the addition of GradeBuilder, which allows the user to develop and add new grades of steel by selecting or adding new algorithms and coefficients. Additional work under Phase 5 was completed in the 4th Quarter of 2004 that included an upgrade to the ROT tracking and thermal models, the addition of "soft" coupling of mill equipment, and the implementation of basic equations for dual phase steels.

The successful result of this project was the final release of the Hot Strip Mill Model (HSMM) as version 6.2. This version allows users to easily set-up their mill configuration, simulate a rolling mill schedule and calibrate the model for a variety of grades of steel. The enhanced HSMM was validated using a multitude of samples from the Enhancement Group steel companies. Excellent agreement was obtained for comparisons between measured mechanical properties and those calculated by the HSMM.

Enhancement features incorporated into version 6.2 of the HSMM that have made it more flexible and practical to use include:

- Improved user interface
- Ability to link all models and track the material through the entire mill
- Improved temperature and force modeling
- Ability to calibrate temperature and force models with plant data
- Ability to adjust microstructure calculation algorithms and coefficients

The supporting steel companies have found outstanding value in the HSMM in saving them time and money for a variety of practical applications. The HSMM continues to be marketed and sold on a global basis as the industry's leading PC-based off-line model for helping steel producers and researchers improve the rolling process.

1 Introduction

This report provides a summary of the Enhancements (Section 2), Validation (Section 3), and Documentation effort (Section 4) that INTEG performed over the life of the entire "Validation of the Hot Strip Mill Model" project. Detailed user's manuals and technical documentation that are provided in Appendices A and B are confidential "Protected Metals Initiative Data" and are available only to the project participants.

2 HSMM Enhancements

The enhancements that were identified as necessary improvements to the HSMM were related to four main categories:

- Software Engineering (section 2.1)
- Practicality in Thermo-mechanical Calculations (Section 2.2)
- Improved Flexibility (Section 2.3)
- Microstructure/Mechanical Property Calculations (Section 2.4)

2.1 Improved Software Engineering

The Hot Strip Mill Model version 4.0 as delivered by UBC was a stand-alone Windows 95 application. It was a composition of a graphical User's Interface and about eight Fortran executables programs and numerous text data files. Each of the Fortran modules represented a particular process area such as the Roughing Mill, Finishing Mill, Runout Table, etc. The interface was an aid for the preparation of input files before launching control to one of the Fortran modules. The graphical user interface was designed in Microsoft's Visual Basic 5.0.

2.1.1 User's Interface

The User's Interface consists of Microsoft-compatible Windows screens, menu selections, buttons, data entry and display fields, charts, etc. that the user interacts with for program control and exchanging data with the Fortran calculation software. Because Microsoft was encouraging its Visual Studio customers to migrate up to its new .NET Framework environment, it was an obvious decision to keep up with the current technology and completely redesign the User's Interface screens using .NET. Some of the changes that went into the redesigned User's Interface software were:

- Divide the Interface screens into five main functional areas:
    - Mill Configuration
    - Grade Calibration
    - Rolling Schedules
    - Data Exporting / Reporting
    - GradeBuilder
- Switch from saving data in text files to Microsoft Access database files
- Add the ability to import rolling schedule data from the plant's database
- Exchange data with the Fortran dynamic link library via well-designed large data structures

Figure 1 provides a picture of the main User's Screen for HSMM version 4.0.

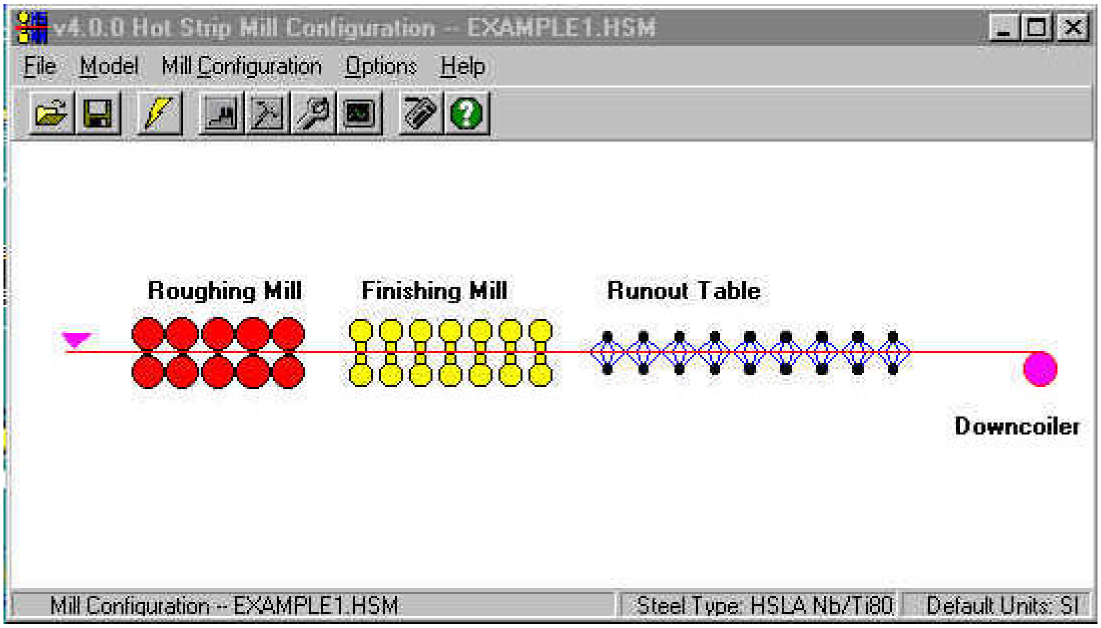


Figure 1 – User Interface for HSMM version 4.0

The HSMM version 6.2 utilizes a user-friendly interface (see Figure 2) allowing each mill to be accurately configured, each rolling schedule to be set-up in detail, each grade of steel to be accurately characterized and the final results to be viewed, charted, reported and exported, as needed. The user interface is divided into the following main areas:

- The **Mill Configuration Screen** allows the user to set-up the rolling mill to be used and includes the furnace area, roughing area (mills, edgers, sprays), heat retention area (coil box, heat panels), finishing area (mills, edgers, sprays), run out table and mill exit area.
- The **Calibration Screen** allows the user to calibrate the model for each grade of steel being simulated. During the overall project set-up, the user selects a specific set of coefficients to be used for the grade of steel being processed via a specific rolling mill schedule.
- The **Rolling Schedule Screen** is used to enter the processing parameters of the piece being modeled and to view the results of the single node and multiple node calculations. The screen allows the user to view and configure the Initial Data, Pass Data, Speed/Time, Shape/Crown, Temperature Data, Rolling Parameters, Microstructure, Run Out Table, Charts and Summary Results.
- The **Data Exporting Screen** allows the user to export data easily from the model to data files that can be easily read by Microsoft Excel or similar software packages for further analysis.
- The **Reporting Screen** is used for printing reports containing Mill Configuration, Calibration, and Rolling Schedule data
- The **GradeBuilder Screens** allows the user to "build" his/her own grade in addition to the nine sample grades characterized for the HSMM

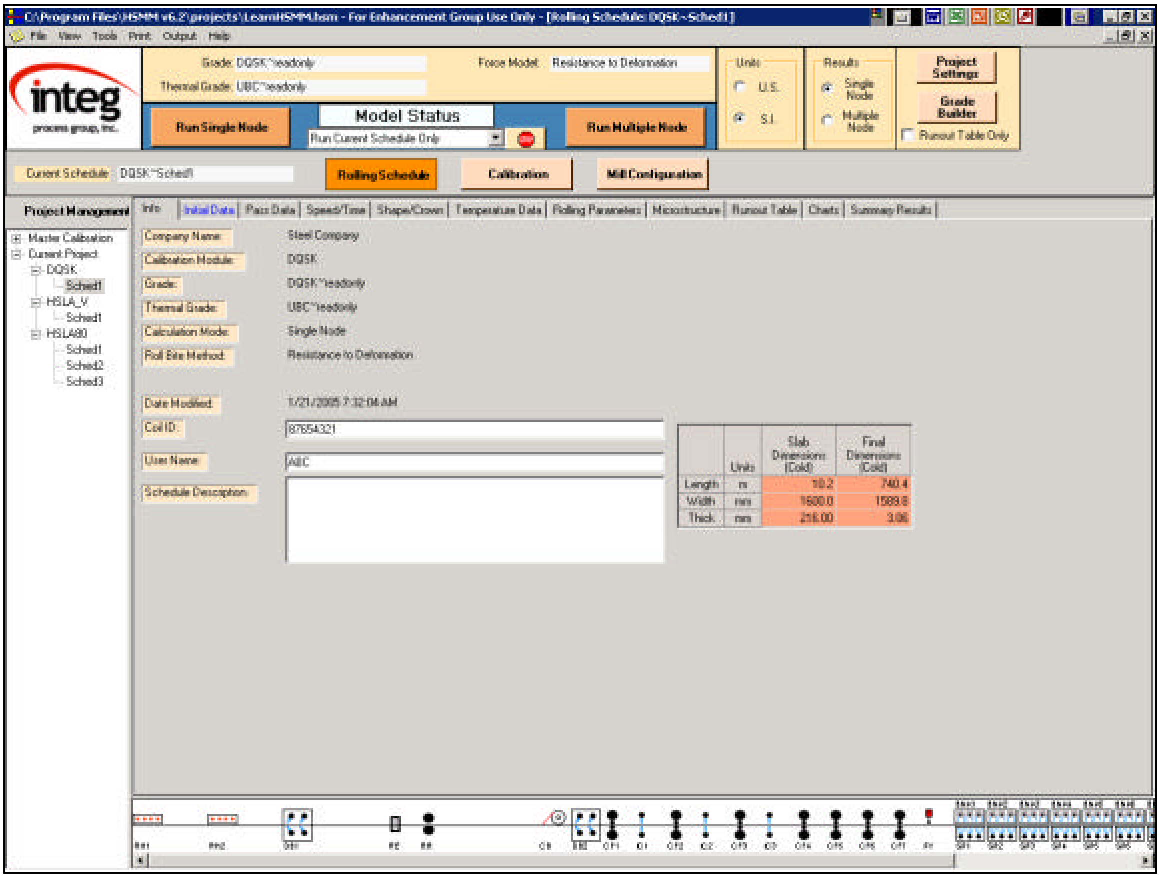


Figure 2 – User Interface for HSMM version 6.2

2.1.2 Fortran Code

The version 4.0 executable programs were built from eight Fortran source files. To make this software more understandable and maintainable several enhancements were made to bring the software up to modern software engineering standards:

- Sub-divide the eight Fortran source files into smaller individual modules
- Eliminate duplication of functionality between the original source files
- Use longer, more descriptive variable names
- Add program block separators and descriptive comments
- Add reasonability checking to module input parameters
- Add calculation error checking to avoid crashes (divide by zero, square root of negative value, exponent over- or underflows)
- Update the code to Fortran 95 standard

Figure 3 illustrates how the software was divided into individual modules to make maintenance of the software easier. A comparison of the version 4.0 Fortran code in Figure 4 and the enhanced Fortran 95 code in Figure 5 shows the improvements that were made in readability and error checking.

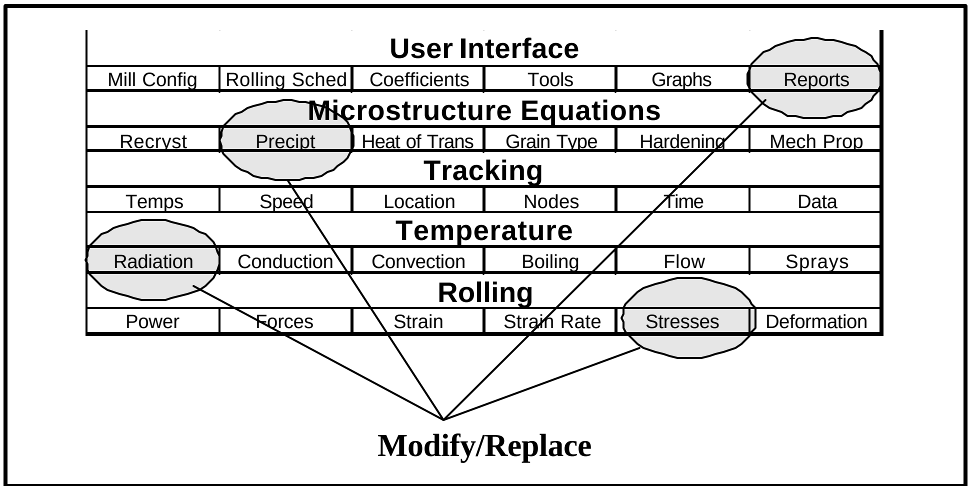


Figure 3 – Modularity of Software Modules for Easy Modification or Replacement

```
C
      SIG1=SIG/9.81
      REDF=REDC(NROLS3)/100.0
      DH=H1-H2
100    FRD = DSQRT (RD / H2)
       DQRT=DSQRT(REDF/(1.0D0-REDF))
       PHI = DTAN(PI*DLOG(1.0D0-REDF)/(8.0D0*FRD)+0.5D0*
    1   DATAN (DQRT)) / FRD
       HNUET = 2.0D0 * RD * (1.0D0 - DCOS (PHI)) + H2
       QP = PI / 2.0D0 / DQRT * DATAN (DQRT) - PI / 4.0D0 -
    1   FRD / DQRT * (DLOG (HNUET / H2) + 0.5D0 *
    2   DLOG (1.0D0 - REDF))
       P = SIG1 * DSQRT(RD * DH) * QP
       ABD = DABS ((P - P0) / P)
     IF (ABD .GT. 1.0D-3) THEN
       RD = R * (1.0D0 + C * P / DH)
       P0 = P
       GOTO 100
     ENDIF
```

Figure 4 – Sample original code without error checking, comments, or descriptive names

```
! ----------------------------------------------------------------------------
!
!   BLOCK 200 - initialize varaibles and calculate Sim's factor
!
! ----------------------------------------------------------------------------

!!  Calculate the roll deformation force.
    SQRT_PARAM = DEFORM_RADIUS / EXIT_DIM
!   Check if SQRT factor is out of range
    IF (SQRT_PARAM < 0.) THEN
!       Exp function out of range
        ERROR_CODE%DESCRIPTION = ERROR_INVALID_CALC
        ERROR_CODE%AREA = MOD_SIMS_GEO_FACTOR
        RETURN
    END IF
    ROLL_DEFORM_FORCE =  SQRT(SQRT_PARAM)

!!  Calculate the frictional force experienced by the roll.
    SQRT_PARAM = DECIMAL_REDUCTION / (1.0 - DECIMAL_REDUCTION)
!   Check if SQRT factor is out of range
    IF (SQRT_PARAM < 0.) THEN
!       Exp function out of range
        ERROR_CODE%DESCRIPTION = ERROR_INVALID_CALC
        ERROR_CODE%AREA = MOD_SIMS_GEO_FACTOR
        RETURN
    END IF
    FRICT_FORCE = SQRT(SQRT_PARAM)

!!  Calculate the angle of contact of the strip at a neutral point.
!!  See equation 2.55 in the steckel mill model theoretical manual.
    CONTACT_ANGLE = ATAN(PI * LOG(1.0 - DECIMAL_REDUCTION) / &
        (8.0 * ROLL_DEFORM_FORCE) + 0.5 * ATAN(FRICT_FORCE)) / ROLL_DEFORM_FORCE

!!  Find the thickness at the neutral point.
    THICK_NEUT = 2.0E0 * DEFORM_RADIUS * (1.0D0 - COS(CONTACT_ANGLE)) + EXIT_DIM

!!  Calculate Sim's geometrical factor
!!  See equation 2.54 in the steckel mill model theoretical manual.
    QP = PI / 2.0 / FRICT_FORCE * ATAN(FRICT_FORCE) - PI / 4.0 - &
        ROLL_DEFORM_FORCE / FRICT_FORCE * (LOG(THICK_NEUT / EXIT_DIM) + &
        0.5 * LOG(1.0 - DECIMAL_REDUCTION))
```

Figure 5 – Sample Fortran 95 code with error checking, comments, & descriptive names

After the Fortran code was sub-divided into smaller calculation modules, flow charts were developed as a permanent record to better understand the program's logic flow. Instead of building a series of executable programs, the Fortran source code was built into a single dynamic link library (dll) file of individual modules that could be called from the User's Interface.

2.2 Improved Practicality in Thermo-Mechanical Calculations

The HSMM version 4.0 ran as seven separate models for the various hot mill areas and mill configuration types: Roughing Mill Model, Reversing Roughing Mill Model, Coil Box Model, Finishing Mill Model, Runout Table Model, Deformation Model, Down Coiler Model, and Steckel Mill Model. The results of each model were not linked to the input of the next successive model. It was discovered that the HSMM version 4.0 lacked the ability to simulate certain hot mill equipment and normal processing conditions. It was also possible for the HSMM to simulate impossible, overly-aggressive reduction conditions. To improve the practicality of the HSMM, several enhancements were incorporated relating to linking all the models together for the entire hot mill, adding various limit checking, and simulating additional pieces of mill equipment.

2.2.1 Material Tracking

As mentioned above, version 4.0 ran each mill area (rougher, finisher, runout table, coiler) as separate models. In version 6.2, the entire hot mill is simulated sequentially from drop out of the reheat or tunnel furnace to exiting into the coiler or cooling bed. Not only did this improve the efficiency of running the model for the user, but also improved the accuracy of the temperature and microstructure calculations by continuously tracking the material's process parameters such as temperature, grain size, precipitation in austenite, retained strain, etc. through all areas of the mill. Three calculations points along the material length were chosen for tracking: the headend, the middle point, and the tailend as shown in Figure 6.

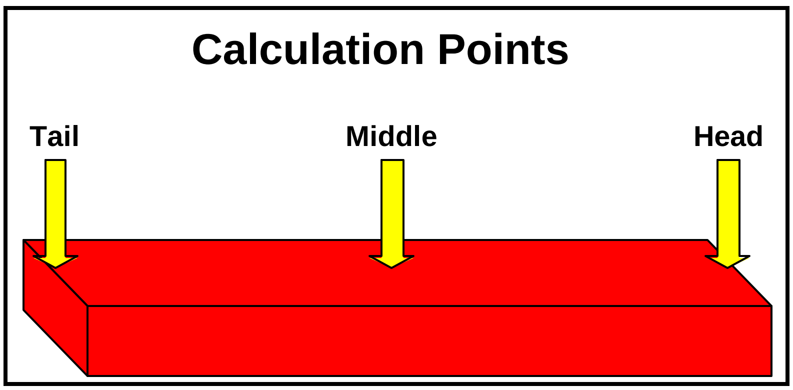


Figure 6 – Tracking Calculation Points

Accurately tracking the timing of the three points through the entire hot mill requires user input of the threading and top speeds during rolling and tables speeds during transfer between stands as well as the stopping distances and delay times for passes at reversing stands. An example speed profile between two individual rolling stands is shown in Figure 7. Applying the actual acceleration and deceleration rates when changing speeds improves the timing and temperature calculations. With more accurate temperature predictions being calculated and provided to the microstructure calculations, more accurate microstructure and mechanical property calculations were also achieved.

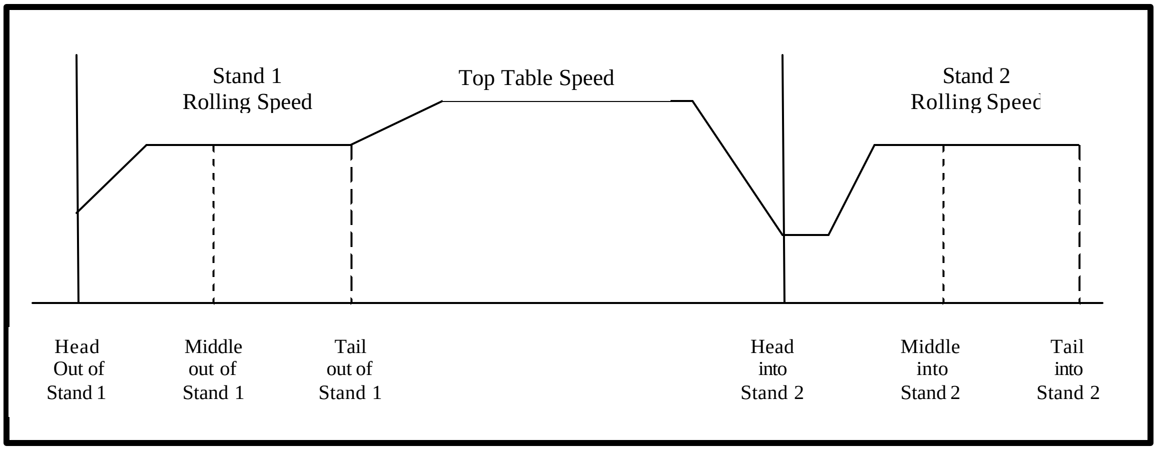


Figure 7 – Speed Profile and Transfer Times between Mill Stands

2.2.2 Force Model

HSMM version 4.0 used the NIST developed equations and coefficients to calculate flow stress 's' and the traditional Sim's geometric factor 'Qp' to calculate the rolling force.

$$F = \frac{2}{\sqrt{3}} s \ Q_p \sqrt{R' \Delta h}\, W \tag{2.1}$$

However, when rolling thick product in the early roughing passes, deformation beyond the arc of roll contact (also known as the peening effect) occurs that results in higher rolling forces. To compensate for this effect, an adjustment was made to the Sim's geometric factor as shown in Figure 8. This adjustment is a function of the roll bite aspect ratio 'a' (contact length L' divided by average thickness).

$$Qp = 0.7924 + 1.778 * \exp(-2.148*a) \text{ for } a < 1.0 \tag{2.2}$$

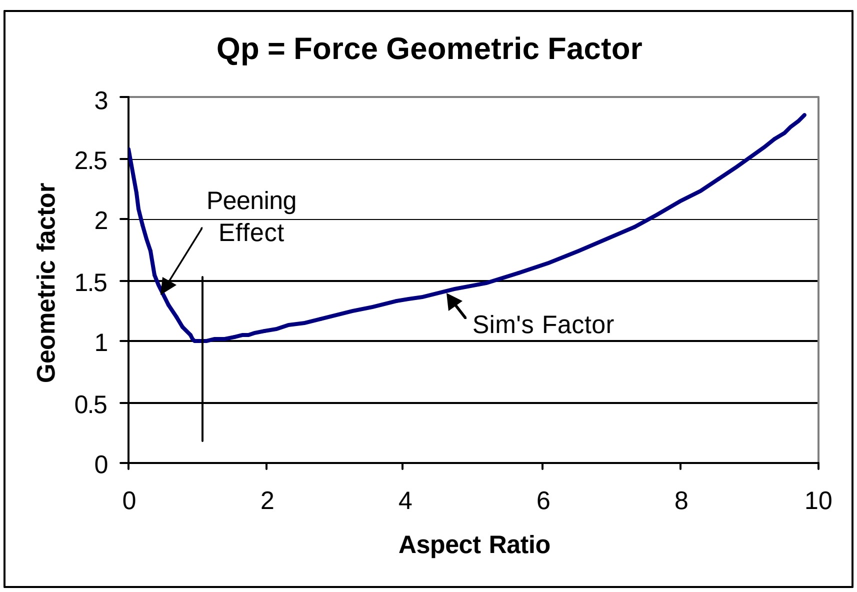


Figure 8 – Force Geometric Factor with Peening Effect

2.2.3 Motor Power Calculations

In addition to roll separating force limitations, other concerns in a hot mill are the limits from the mill stands' motor power and torque. It is a futile exercise to develop a new rolling practice for a product that achieves the target mechanical properties, but the mill doesn't have the power to produce it. HSMM version 6.2 was enhanced with the addition of optional motor power and torque calculations as shown in Figure 9. These calculations are optional to the HSMM user because power calculations require a number of motor data parameters (rated power, RPMs, maximum load ratio, gear ratio of the gear box, etc) be input for each rolling stand.

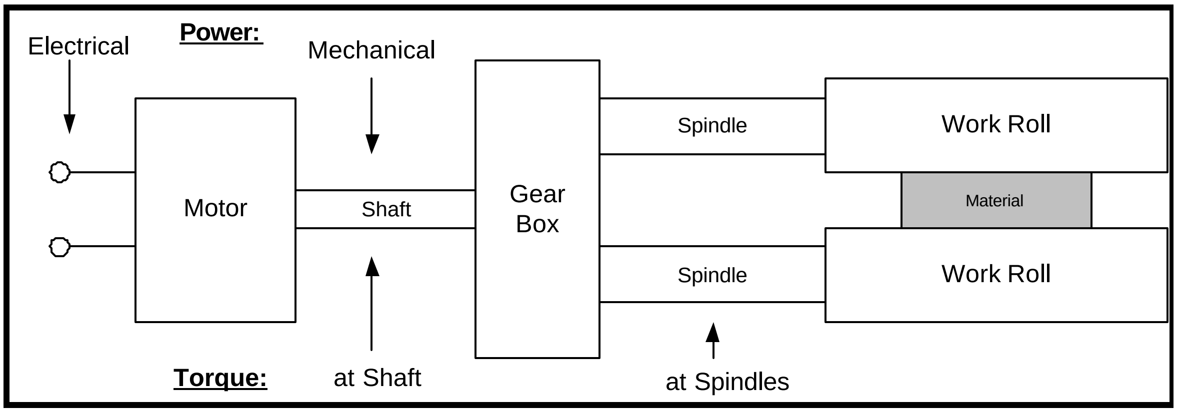


Figure 9 – Mill Stand Drive showing Motor Power and Torque Calculations

Before calculating motor power, the total rolling torque 'M' is calculated from the rolling force 'P' in kN and the lever arm 'a' in mm and multiplied by 2 to consider both work rolls.

$$M = \frac{2 * P * a}{1000} [kN - m] \tag{2.3}$$

The total rolling torque is affected when entry and/or exit tension on the material is present. In this calculation, tension not only lowers the rolling force and therefore the rolling torque, but entry tension S1 increases the rolling torque while exit tension S2 decreases it.

$$\mathrm{M} = \frac{2 * \mathrm{a} * W * L'}{1000} * \frac{(K - s_{avg})}{1000} + \frac{R}{1000} * \frac{(S_1 - S_2)}{1000} [kN - m] \tag{2.4}$$

s_{avg} is the average specific tension in MPa.

$$s_{avg} = b * s_1 + (1 - b) * s_2 \tag{2.5}$$

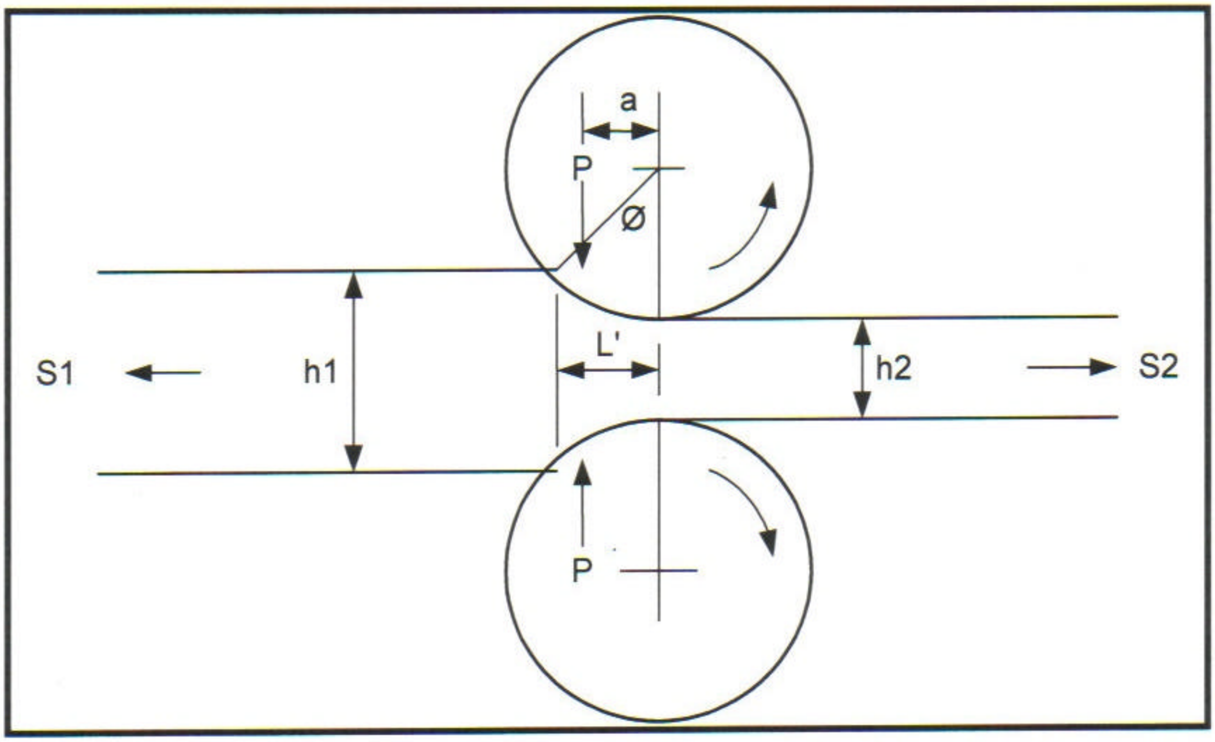


Figure 10 – Roll Bite illustrating contact length L', bite angle θ, roll force P, and tensions S

The lever arm is the distance from the work roll center line to a point located along the roll bite contact length L′ where the entire vertical force vector can be considered to exist for calculating the rolling torque (see Figure 10). The lever arm is calculated from the lever arm coefficient 'm' that is a function of the roll bite geometry (roll diameter D and exit thickness h2).

$$a = m * L' \tag{2.6}$$

$$m = c1 + c2 * \exp\left(\frac{c3 * D}{2 * h2}\right) \tag{2.7}$$

where coefficients c1, c2, and c3 have been determined. A graph of the lever arm function is provided in Figure 11.

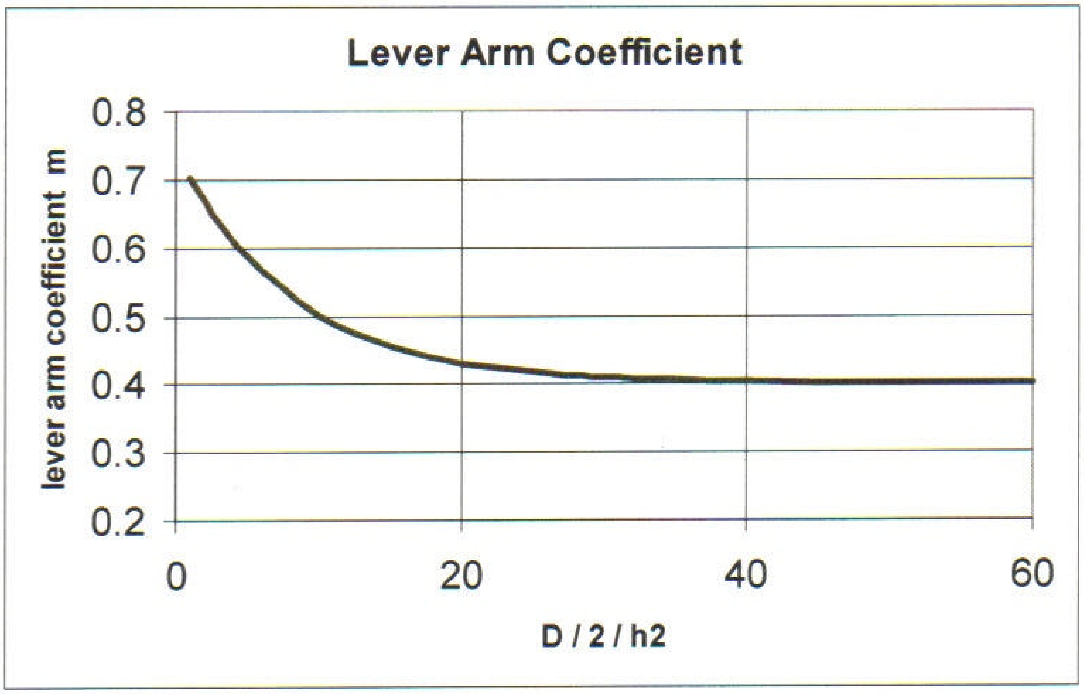


Figure 11 – Lever Arm Coefficient 'm' as a Function of Roll Bite Geometry

The torque at the motor shaft is the torque at the rolls after transfer through any gear box with a gear ratio 'GR' and a mechanical efficiency 'η'. Because there are frictional losses in a gear box, it has an efficiency η that is normally between 0.9 and 1.0. If there is no gear box, the gear ratio = 1.0 and η = 1.0.

$$M_{motor} = \frac{M}{GR * \eta} \tag{2.8}$$

The mechanical power that must be delivered at the shaft of the motor to roll the material is a function of the torque at the roll and the roll angular speed. The mechanical power is compared to the motor rated power to determine the load ratio. Because of the electrical losses in the motor, the electrical power (volts x amps) input to the motor is greater than the mechanical power output.

$$KW = \frac{M * \omega_{roll}}{\eta} = \frac{M * v * 1000}{R * \eta} \tag{2.9}$$

If the power calculations are turned "ON", HSMM version 6.2 calculates the required power and torque for each reduction and warns the user whenever the calculated values exceed the maximum limits or are within 5% of the limit.

2.2.4 Width Changes

Besides developing the proper mechanical properties, the purpose of hot rolling is to reduce the thickness of the slab to the final sheet or plate thickness while making the product length proportionately longer. However, in flat rolling the material also gets wider due to spreading. To counteract spreading, many hot mills have edging equipment to take width reductions, usually in the roughing stage while the work piece is still thick enough to prevent buckling. HSMM version 6.2 has incorporated models for spreading, edging, and spreading after the edging. Modeling the correct width results in better force predictions at the horizontal stands as well as allowing the HSMM to be used for edging capability studies.

Spreading due to horizontal rolling is a function of width and thickness into the roll bite W1 and H1, thickness exiting the roll bite H2, and roll diameter D.

$$A = \exp\left(c1 * \left(\frac{W1}{H1}\right)^{c2} * \left(\frac{W1}{L'1}\right)^{c3*\frac{W1}{H1}} * \left(\frac{H1}{R}\right)^{c4*\frac{W1}{H1}} \right) \qquad Spread = W1 * \left[\left(\frac{H1}{H2}\right)^{A} - 1 \right] \quad (2.10)$$

where coefficients c1, c2, c3, and c4 have been determined

During width reduction by edging, some of the material will result in elongation of the work piece and the remainder will cause bulging at the material edges. Rolling in a horizontal stand after edging will force some of the bulge into elongation and some of it will spread back as increased width and is called recovery. Recovery is a function of previous width draft ΔW, width and thickness into the edger W1 and H1, width exiting the edger W2, and edger roll radius Re.

$$B = \exp\left(c1 * \left(\frac{\Delta W}{W1}\right)^{c2} * \left(\frac{H1}{\mathrm{Re}}\right)^{c3} * \left(\frac{\mathrm{Re}}{W1}\right)^{c4} * \left(\frac{W1}{W2}\right)^{c5} \right) \qquad \mathrm{Recovery} = B * \Delta W \quad (2.11)$$

where coefficients c1, c2, c3, c4, and c5 have been determined

If the edger rolls are the grooved design type (with a top and bottom collar) and the material is at a thickness to fill the groove, then the bulge created during edging will be forced inward from the edge. The recovery that occurs after horizontal rolling will be less with grooved rolls and the edging process more efficient than with normal flat edger rolls as shown in Figure 12.

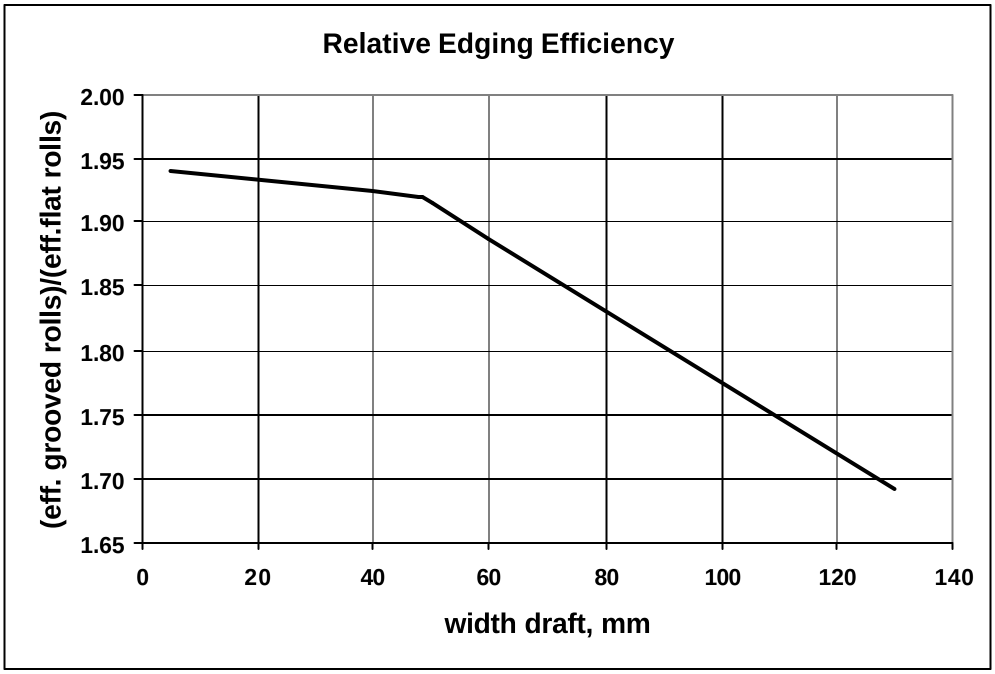


Figure 12 – Increased Edger Efficiency with Grooved Edger Rolls

2.2.5 Limit Checking

In addition to the power checking that was described in section 2.2.3, HSMM version 6.2 has incorporated a system of checking both user-entered and calculated values against maximum and/or minimum limit values. These limits are configured by the user and many are of these limits are optional. A list of any limit violations is displayed to the user.

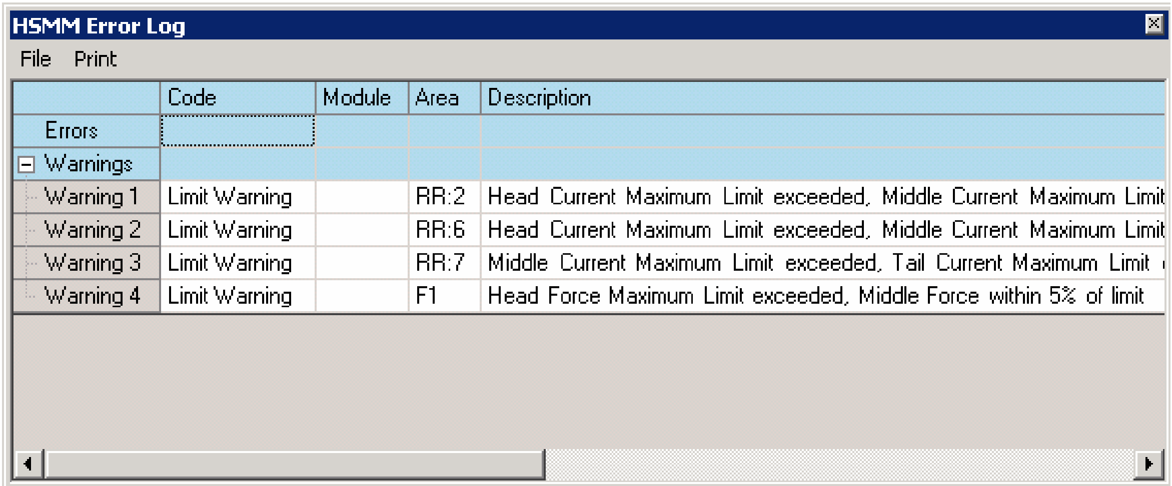
Entered parameters that are limit checked:

- Slab temperatures
- Slab dimensions
- Roll diameters
- Work roll speeds
- Table speeds

Calculated parameters that are limit checked:

- Material lengths and widths
- Bite angles
- Rolling forces
- Rolling torques
- Motor output powers
- Edger buckling

Error and limit warning messages are displayed to the user as shown in Figure 13.



HSMM Error Log

File Print

	Code	Module	Area	Description
Errors				
Warnings				
Warning 1	Limit Warning		RR:2	Head Current Maximum Limit exceeded, Middle Current Maximum Limit
Warning 2	Limit Warning		RR:6	Head Current Maximum Limit exceeded, Middle Current Maximum Limit
Warning 3	Limit Warning		RR:7	Middle Current Maximum Limit exceeded, Tail Current Maximum Limit
Warning 4	Limit Warning		F1	Head Force Maximum Limit exceeded, Middle Force within 5% of limit

Figure 13 – Error and Warning Messages

2.2.6 Added Crown and Shape Models

Even though the hot mill can roll a particular product within its own limits, the product may not be salable if its shape (flatness) is unacceptable. Another level of practicality was added to version 6.2 with the incorporation of the crown and shape models. These models can be turned on by the user to calculate the crown (profile) on the work piece after each reduction. The exit crown of the work piece is calculated from the deflection of the roll stack due to the rolling load, the crowns on the work and backup rolls, and any applied mechanical bending forces. To maintain a flat product with good shape, its relative (%) crown can change only so much until the internal stresses either cause buckles down the center of the strip or waves down the edges. The amount of allowed crown change has been defined by an upper and lower limit that produces a shape "envelope" as shown in Figure 14.

$$\Delta c = \frac{c1}{h1} - \frac{c2}{h2} \tag{2.11}$$

where c1 = entry crown, c2 = exit crown

$$\text{(Edge Wave)} \quad -80\left(\frac{h}{w}\right)^{1.86} > \Delta c > 40\left(\frac{h}{w}\right)^{1.86} \quad \text{(Center Buckle)} \tag{2.12}$$

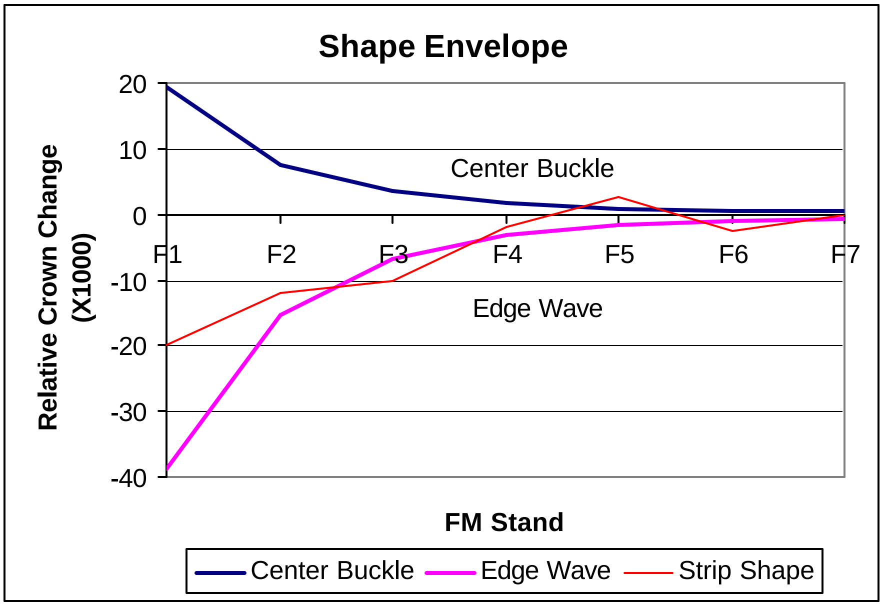


Figure 14 – Shape Envelope and Calculated Curve

By adjusting the reductions in the finishing mill and the bending forces (if available) the material shape can be made flat or at least improved.

2.2.7 Additional Mill Equipment

Enhancing the HSMM for version 6.2 included expanding the temperature models to simulate some common mill equipment items such as heat covers (also known as thermal covers, thermal panels, table covers, etc) and cooling beds for plate products.

Heat Covers

Heat covers are modeled by applying an elevated ambient temperature input for the headend and a calculated ambient temperature for the tailend based on the headend temperature that pre-heats the covers. Both top-and-bottom and top-only heat covers can be modeled.

Cooling Bed

A cooling bed is available for plate products to be sent after the Runout table for simulation of radiation and convection cooling at the mill ambient temperature. Simulation of forced convection, however, was not included.

2.3 Improved Flexibility

Several of the enhancements to HSMM version 6.2 originated from the need to provide flexibility to the user in making choices and adjustments to help improve the model's results and handle more processing conditions.

2.3.1 Added Single-Node Calculations

The HSMM version 4.0 used the implicit finite difference method for calculating temperatures at multitude nodes through the thickness down the center of the work piece. This calculation method has been preserved in version 6.2 and calculates 101 nodes through the steel thickness and 10 nodes through each top and bottom scale layer. Because the total calculation time for a complete hot mill simulation using this multiple node approach can be 2 to 3 minutes (depending on computer speed and the complexity of the mill configuration), a single-node model was introduced to allow for "rapid calculations".

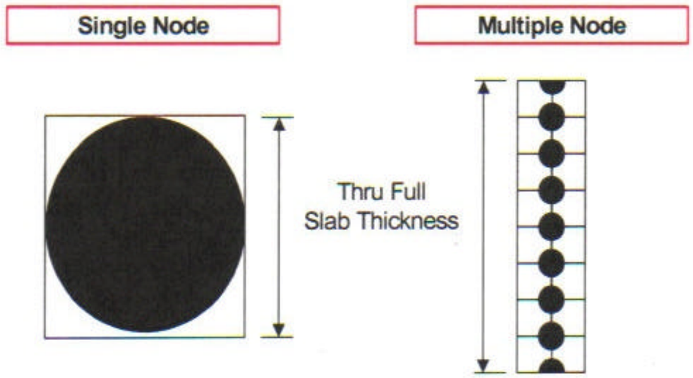


Figure 15 – Single vs. Multiple Node Calculations

The single-node method calculates all the same thermo-mechanical and microstructural parameters as the multiple-node model, but only as one "average" value for the entire thickness instead of the multiple-node method's 121 nodes (See Figure 15). A new set of tunable thermal models were introduced for calculating bulk average temperature changes through the mill, but the same microstructure models were applied. Because the single-node method dramatically reduces the number of calculations, calculation time is typically around 5 to 10 seconds. Both methods calculate data for the head, middle, and tail of the work piece and each method is completely independent of the other and is calibrated with separate tuning coefficients.

2.3.1.1 Radiation Loss

$$\Delta Trad\ [C] = 2 * (1/h + 1/w) * S * \varepsilon / \rho / Cp / [(T + 273.15)^{\wedge}4 - (Tamb + 273.15)^{\wedge}4] * \Delta t \quad (2.13)$$

where: S = Stephan-Boltzman constant
ε = emissivity

2.3.1.2 Roll Conduction Loss

$$\Delta Twrc\ [C] = 4 * k / \rho / Cp / havg * (T - Tr) * sqrt(L' / \pi / \alpha / v) \quad (2.14)$$

where: k = roll conductivity
α = roll diffusivity

2.3.1.3 Deformation Gain

$$\Delta Tmec\ [C] = K * \eta m\ / \rho / Cp * \ln(h1/h2) * 10^{\wedge}6 \quad (2.15)$$

$$\eta m = a + b * \exp(-c * K / \rho / Cp * \ln(h1/h2) * 10^{\wedge}6)$$

2.3.1.4 Water Spray Loss

$$\Delta Twat\ [C] = 2 * k / \rho / Cp / h * (T - Tw) * sqrt(WatCL / \pi / \alpha / v) \quad (2.16)$$

where: k = material conductivity
WatCL = contact length of the water spray
α = material diffusivity

2.3.1.5 Runout Table Spray Loss

$$\Delta Twat\ [C] = 2 * k / \rho / Cp / h * (T - Tw) * WatCL/WatCL0\ / v \tag{2.17}$$

Because the single-node method can calculate results that are consistent with those from the multiple-node method but much more rapidly, it has proven to be a valuable addition for making the HSMM more efficient for the user. The multiple-node method is still available when the user requires the detailed temperature and microstructure profiles through the material thickness.

2.3.2 Added Resistance to Deformation Force Model

The NIST flow stress calculations in version 4.0 utilized a series of equations initially developed by NIST. These equations are dependent on temperature, austenite grain size, strain, and strain rate with associated coefficients that were developed for each of the eight characterized steel grades.

For version 6.2, a resistance to deformation force model was added to allow the user to generate a curve calculated from existing rolling mill data. The resistance to deformation of the rolled material (K_W) is defined as the total roll separating force (F) divided by the projected area (A = W * L) between the work roll and the work piece when rolled without tension.

$$K_W = \frac{F}{A} \tag{2.18}$$

When the material's microstructure restoration process time is shorter than the gap time between rolling passes, the resistance to deformation depends mainly on the temperature of the rolled material and the geometry of the roll bite. Therefore, it is defined as the product of the normalized resistance to deformation (K_N), a geometric factor (k_G), and a temperature factor (k_T).

$$K_W = K_N * k_G * k_T \tag{2.19}$$

The geometric factor (k_G) is a function of the average aspect ratio (α) in the roll bite. The aspect ratio is defined as the contact length of the material in the roll bite (L) divided by the average material thickness (h_A).

Two equations are used to define the function for k_G, one for aspect ratios below αc, and one for aspect ratios above αc, where αc is determined by the intersection of the two equations. Below αc the k_G function takes non-homogeneous compression into account where the plastic deformation zone extends outside of the region defined by the arc of contact. The graph of the following two equations is shown in Figure 16.

$$k_G = b1 * a + c1;.for.a <= a_c \quad (2.20)$$

$$k_G = a2 * a^2 + b2 * a + c2;.for.a > a_c \quad (2.21)$$

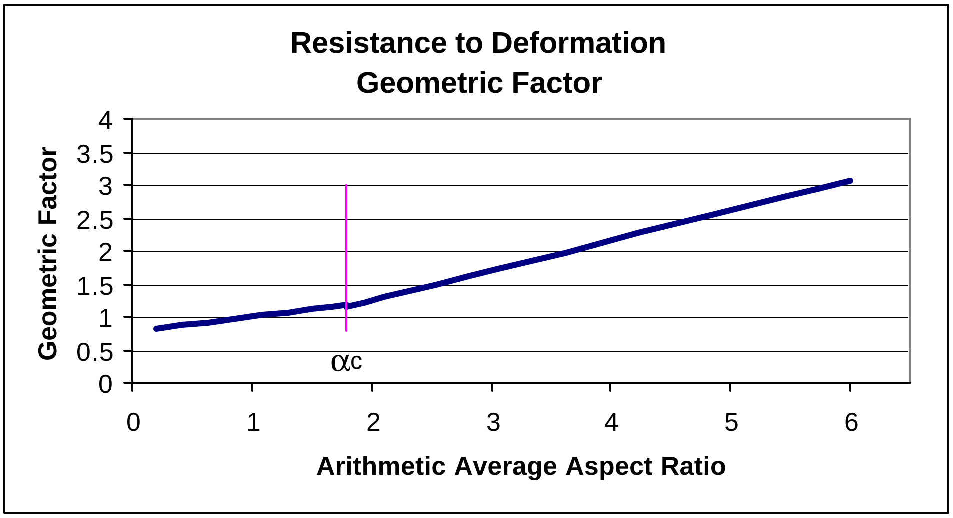


Figure 16 – Resistance to Deformation Geometric Factor

The temperature factor (k_T) is a function of the temperature difference between the selected Normalized Temperature (T_N) and the material temperature. The graph of the following two equations for the temperature factor is shown in Figure 17.

$$k_T = 1 + b1 * (T_N - T); \text{ for } T >= T_N \quad (2.17)$$

$$k_T = 1 + b2 * (T_N - T); \text{ for } T < T_N \quad (2.18)$$

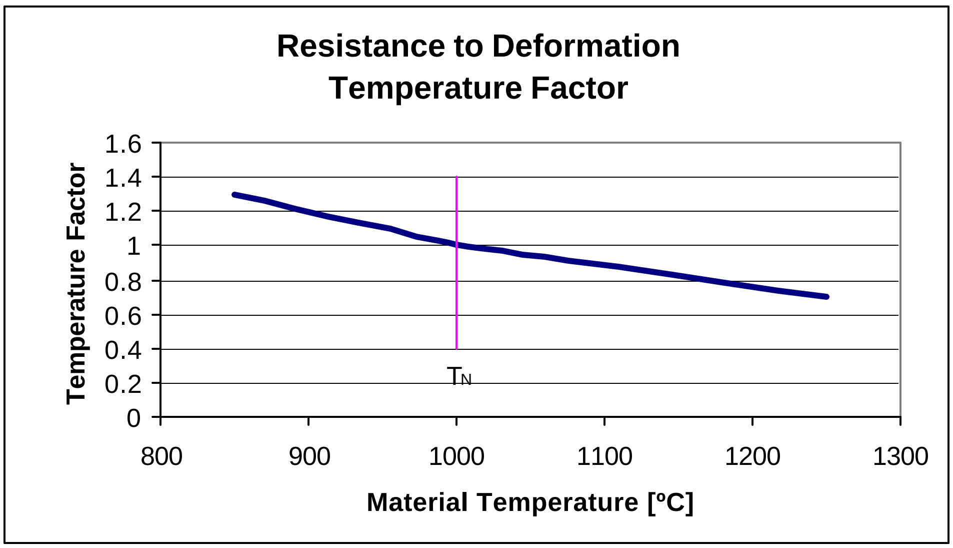


Figure 17 – Resistance to Deformation Temperature Factor

The normalized resistance to deformation (K_N) is the value of resistance to deformation of the rolled material at the selected normalized temperature and at a normalized aspect ratio which has a value of 1.

This method is semi-empirical, but allows the model to accurately calculate the force predictions by using plant data from previously processed coils for any grade of steel. Once the model is calibrated using this method, new rolling schedules for the same grade can be accurately simulated for conducting what-if analysis.

The user has the choice of which rolling force model to use, either flow stress or resistance to deformation.

2.3.3 Added Other Flow Stress Models

Both the Shida and Medina flow stress calculation methods were added for using grades of steel not characterized in the lab for the NIST developed equations nor were previously rolled in the user's mill to provide data for the resistance to deformation calibration. Like the NIST flow stress method, these methods define the flow stress of steels during hot plastic deformation as a function of temperature, strain, strain rate, and austenite grain size. However, what distinguishes these two flow stress models and makes them useful is that they calculate flow stress also as a function of the steel's chemical composition.

The Shida flow stress model was developed by S. Shida of Hitachi Research in 1974. This model is applicable to C-Mn steel grades that may contain a small amount of microalloying elements. Figure 18 is a graph illustrating the effect of changing carbon content of the Shida flow stress.

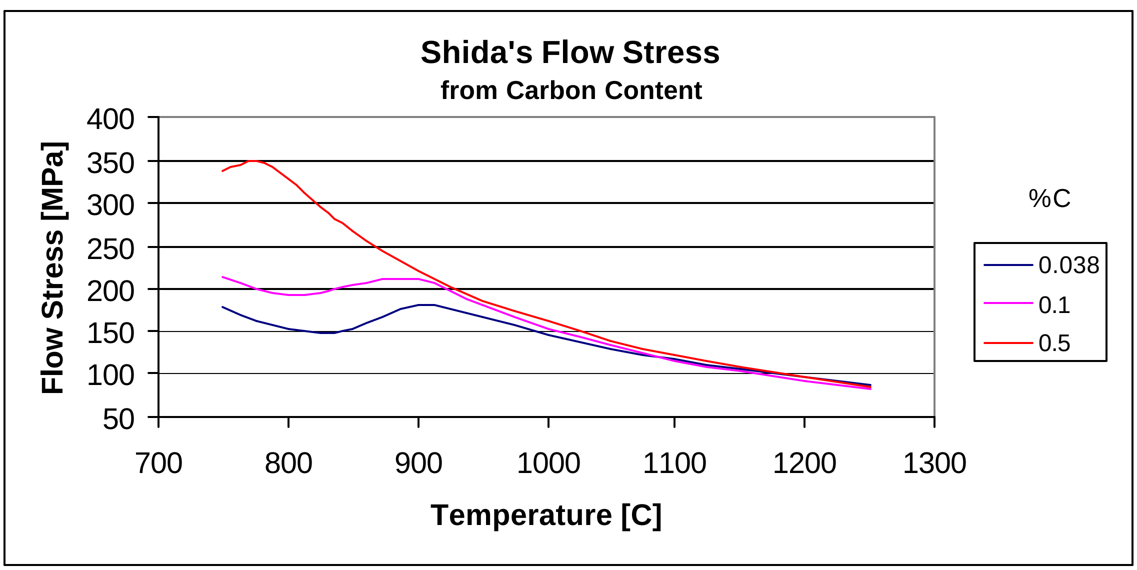


Figure 18 – Shida Flow Stress as Function of %Carbon Content

The Medina flow stress model was developed by S.F. Medina and C.A. Hernandez in 1996. This model can be applied to C-Mn steels as well as those containing microalloys such as Vanadium (V), Titanium (Ti), and Niobium (Nb). A graph of the Medina flow stress for a HSLA-50 grades is shown in Figure 19.

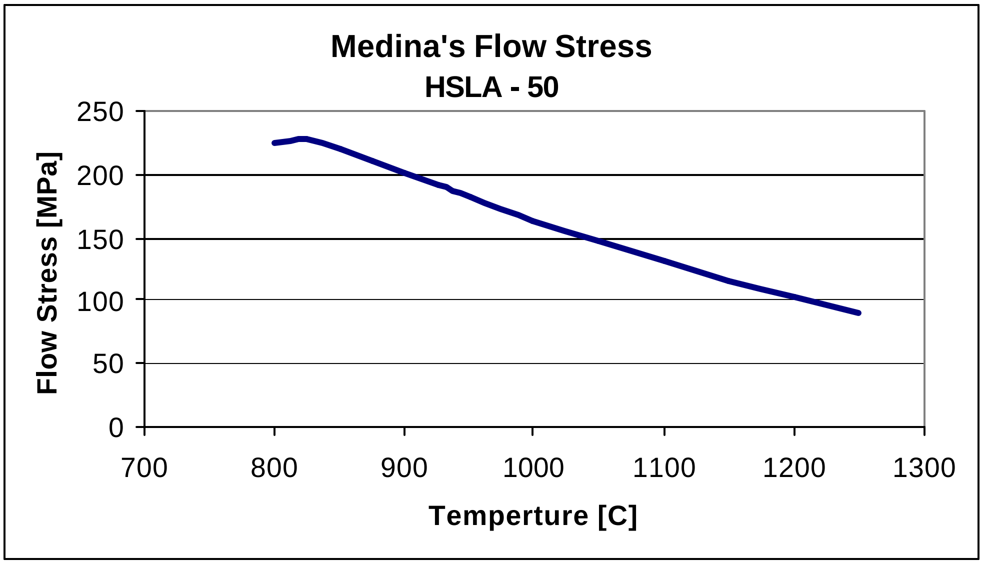


Figure 19 – Medina Flow Stress for HSLA-50

2.3.4 Added Temperature Tuning Coefficients

The ability of the HSMM to accurately simulate rolling loads and final mechanical properties is directly dependent on its ability to accurately simulate the correct material temperature evolution through the hot mill. Temperature evolution in the material mainly involves the effects of radiation, conduction to the work rolls, conduction to water sprays, and heating from deformation. Although the HSMM requires the user to input a number of parameters that characterize the mill equipment and operating conditions, there will always be a set of unaccountable factors that are difficult, if not impossible or impractical, to include in any thermal model (e.g. the cooling effect of roll cooling water that reaches the strip or the effect of a water spray that remains partially plugged). Because these variable factors cannot be modeled, other thermal models need to be adjusted with tuning coefficients to compensate for these factors and produce reliable results. Separate thermal model tuning coefficients and multipliers were added for the single-node and multiple-node models as shown if Figures 20 and 21, respectively.

Common | Single Node | Multiple Node | Mechanical Properties | Rarely Modified

Description	Units	Value
Mill Areas Tuning Coefficients		
Radiation Effect		0.80
Conduction to Work Roll (Roughing Area)	W/m/C	6.00
Conduction to Work Roll (Finishing Area)	W/m/C	9.50
Descale Water Thermal Conductivity (Roughing Area)	W/m/C	20.00
Descale Water Thermal Conductivity (Finishing Area)	W/m/C	22.00
Interstand Cooling Water Thermal Conductivity	W/m/C	8.00

Description	Units	Value
Runout Table Tuning Coefficients		
Water Thermal Conductivity	W/m/C	12.00
Top Header Calibration Factor		1.00
Bottom Header Calibration Factor		0.60
Top Header Water Effect		0.90
Low Coiling Temperature Coefficient		1.000

Figure 20 – Single Node Thermal Model Tuning Coefficients

Common | Single Node | Multiple Node | Mechanical Properties | Rarely Modified

Description	Units	Value
Mill Areas Tuning Coefficients		
Radiation HTC Factor		0.80
Conduction HTC Factor to Work Roll (Roughing Area)		4.00
Conduction HTC Factor to Work Roll (Finishing Area)		2.00
Descale Water HTC Factor (Roughing Area)		2.00
Descale Water HTC Factor (Finishing Area)		1.00
Interstand Cooling Water HTC Factor		1.00

Description	Units	Value
Runout Table Tuning Coefficients		
Top Boiling Zone HTC Multiplier (Zones 1,4)		1.00
Top Impingement Zone HTC Multiplier (Zones 2,3)		1.00
Top Spray Impingement Efficiency Multiplier		0.90
Bottom Impingement Zone HTC Multiplier (Zones 2,3)		1.00
Low Coiling Temperature Coefficient		1.000

Figure 21 – Multiple Node Thermal Model Tuning Coefficients

The HSMM can plot calculated temperatures as well as entered measured temperatures entered by the user. Measured temperatures may be recorded in Engineering Logs or stored in the plant's database. The source of these temperatures may be from pyrometer readings at various locations in the mill or they may be calculated by the plant's on-line Level 2 computer at each stand or pass. From the HSMM temperature chart of calculated vs. measured values, the user can adjust the thermal model tuning coefficients in an iterative process of running the model and adjusting the tuning value until the calculated values match the measured ones as shown in Figure 22.

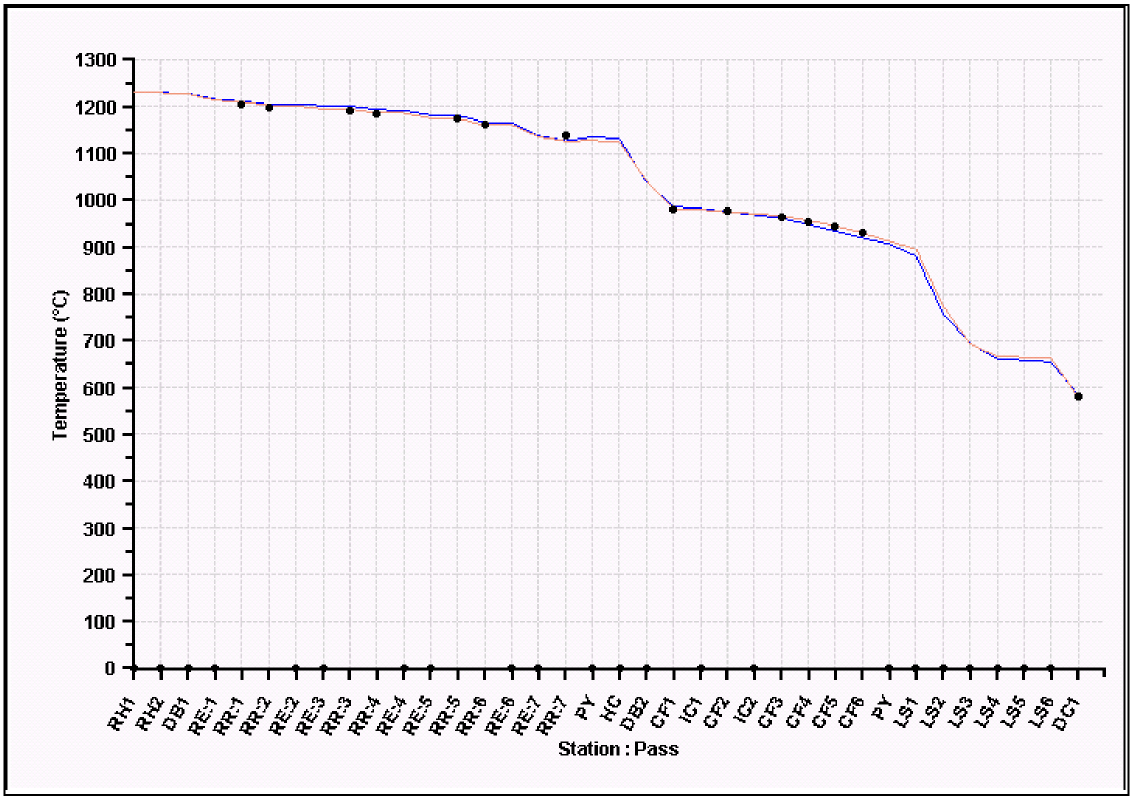


Figure 22 – Chart of Calculated (lines) vs. Measured (dots) Temperatures for Tuning

2.3.5 Added Automatic Force Model Calibration

Like the thermal models need for a tuning method to be more accurate, the three flow stress methods needed a tuning method to make the force model more accurate. All three methods consider the temperature, strain, strain rate, and austenite grain size for their calculation of flow stress. If the force model is using one of the flow stress methods and it is not providing accurate force predictions, the difficulty is determining which flow stress coefficients to adjust.

To simplify the calibration procedure, it was decided to only adjust the flow stress based on temperature and to let the HSMM calculate its own calibration coefficients for each grade. By entering measured roll bite entry temperatures and rolling forces into the HSMM for one or more rolling schedules of the same grade, the flow stress calibration procedure can be initiated by the click of a button. This procedure calculates the ratios of the measured to the calculated rolling forces and then performs a second order polynomial regression on this set of ratios vs. temperatures to determine the A, B, and C coefficients for the flow stress tuning multiplier. An example regression calculation and graph is provided in Figure 23 and the flow stress calibration screen is shown in Figure 24.

$$Flow\ Stress\ Multiplier = A*T^2 + B*T + C \tag{2.18}$$

Temp	Fmeas	Fcalc	Ratio = m/c
1225	1505	1500	1.0033
1220	1750	1735	1.0086
1210	2135	2164	0.9866
1200	2080	2099	0.9909
1180	2165	2206	0.9814
1150	2215	2243	0.9875
1050	2630	2769	0.9498
1030	2590	2711	0.9554
1005	2410	2549	0.9455
990	2095	2228	0.9403
970	1690	1802	0.9378
950	1450	1562	0.9283

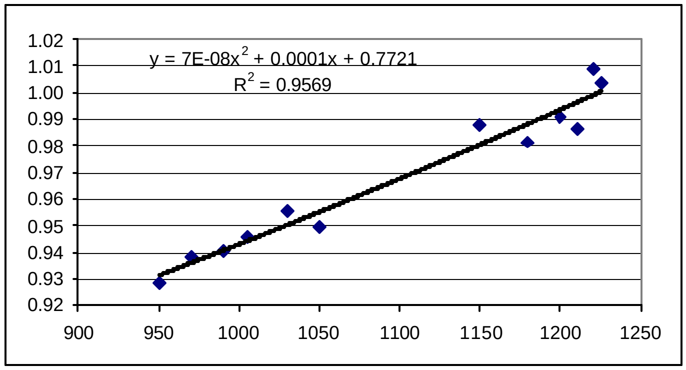


Figure 23 – Flow Stress Multiplier Regression

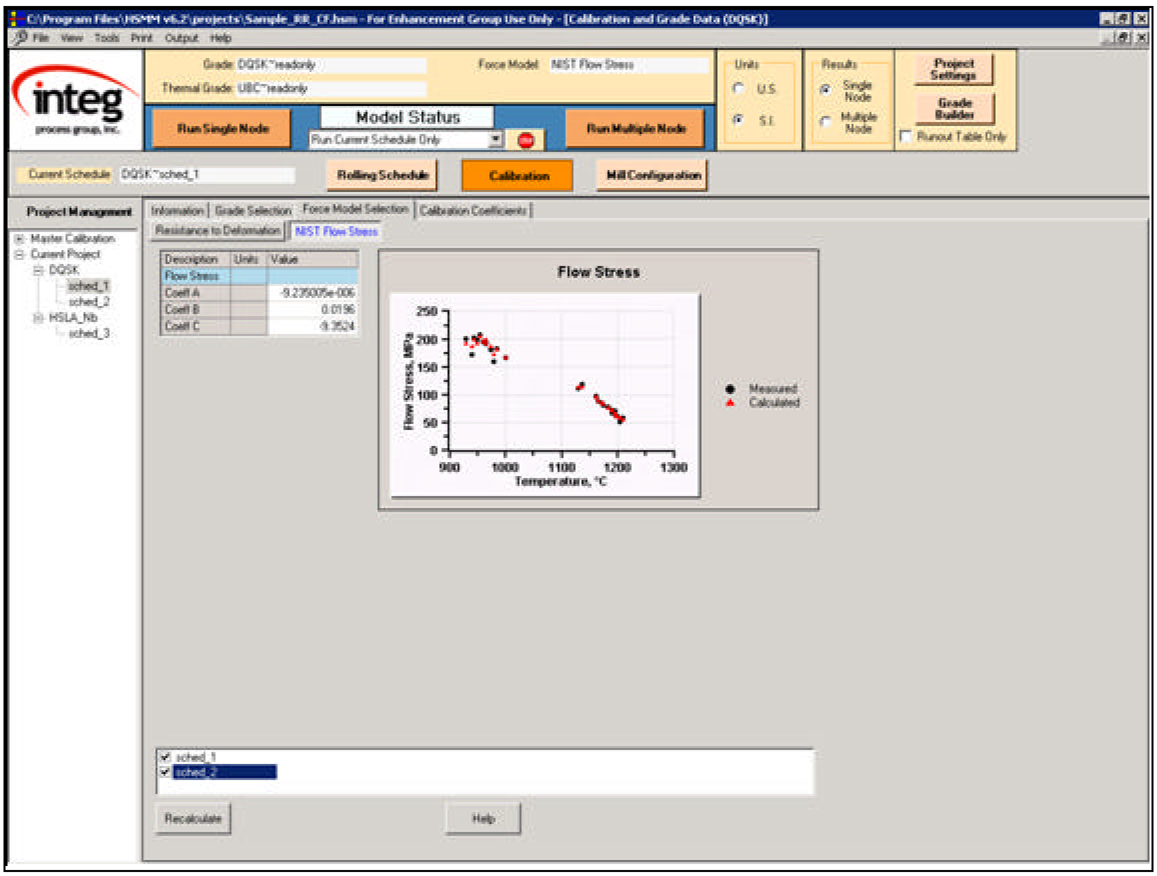


Figure 24 – Flow Stress Calibration Screen

Once a grade is calibrated with its own set of A, B, and C calibration coefficients, the flow stress multiplier function produces multiplier values within a range around 1.0 that adjust the flow stress and force calculations to better match the measured forces. New rolling schedules created for the grade can be expected to have improved force predictions.

2.3.6 Added Plant Database Importing

The ability to import data from a plant database and automatically create a Rolling Schedule was added in version 6.2. This enhancement allows the user to simulate a previously rolled coil without having to manually enter the rolling parameters, such as thicknesses, speeds, measured forces, etc. To implement this feature the user must set up an ODBC connection to the plant database via Administrator Tools in his Windows Control Panel. Then by invoking a query into the plant database, three tables of data must be generated in a format required by the HSMM. Once the tables are created, the HSMM Database Link utility screens are used to import data and create new rolling schedules as shown in Figure 25.

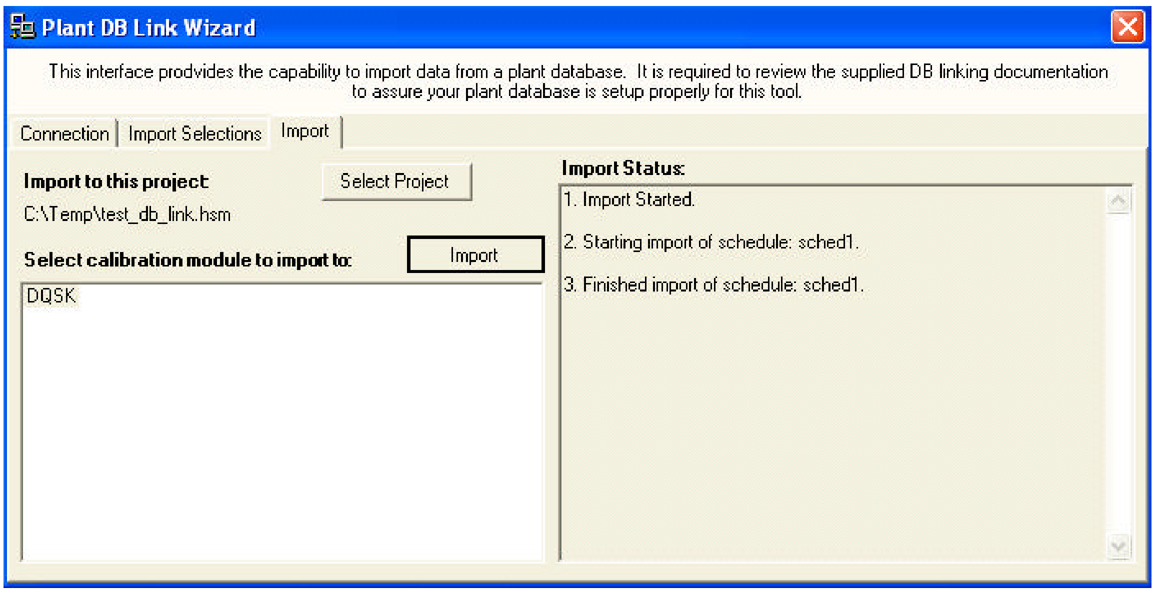


Figure 25 – Plant Database Link

2.3.7 Handle Low Coiling Temperatures

The runout table model for HSMM version 4.0 was developed and tested for normal coiling temperatures down to 550° C. For simulating certain advanced high strength steels (AHSS), much lower coiling temperatures are required to produce the desired bainite and martensite phases. It was discovered during HSMM simulations that the runout table models for both the multiple node and single node models could not be tuned to simultaneously produce the intermediate temperatures and low coiling temperatures that were actually observed in plant trials. The plant data showed there was very rapid cooling of the material at temperatures below 450° C.

To increase the heat transfer in this low temperature region, a multiplier was introduced into version 6.2 that could be tuned to match actual data. This low coiling temperature multiplier is an equation that is a function of temperature and a tuning factor ‘A’. Separate tuning factors are applied to the single node and multiple node models.

2.4 Improved Microstructure/Mechanical Properties Calculations

2.4.1 Allow Chemistry Adjustments

The microstructure evolution and final mechanical properties models developed by UBC for version 4.0 were based on eight grades of steel with specific chemistries. These models contained equations with coefficients determined from lab tests. Many of these equations were chemistry-dependent, but the chemistry values applied to these equations were fixed for each of the eight grades that could be selected.

The first step in version 6.2 in making the microstructure evolution models more flexible was to allow the user to enter the actual chemistry of the grade he/she is simulating. After entering the actual User Chemistry as shown in Figure 26, the user then selects the grade with chemistry closest to the entered chemistry. The grades available for selection include the nine sample grades and any others that have been built using GradeBuilder as described in Section 2.4.2. By allowing the user to enter a chemistry that differs somewhat from the selected grade's chemistry, the microstructure results are generally improved. If the user enters chemistry values that deviate significantly from the selected grade, a message is displayed that warns the user that the microstructure results may be suspect.

	C %	Mn %	P %	S %	Si %	Cu %	Ni %	Cr %	Mo %	Nb %	V %	Ti %	Al %	N %	B %
User Chemistry	0.0700	0.6700	0.0100	0.0040	0.0500	0.0400	0.0140	0.0210	0.0030	0.0440	0.0000	0.0000	0.0000	0.0048	0.0000
Grade Base Chemistry	0.0820	0.4800	0.0120	0.0050	0.0450	0.0260	0.0160	0.0230	0.0000	0.0360	0.0020	0.0020	0.0240	0.0054	0.0000

Figure 26 – User Chemistry Field

2.4.2 Added GradeBuilder Module

The next step in version 6.2 in making the microstructure evolution models more flexible was to allow the user to "build" his/her own grade in addition to the nine sample grades. The purpose of adding the GradeBuilder module to the HSMM was to change the user's view of the microstructure models from being a rigid "black box" to being an open configuration panel for building a new grade or modifying an existing grade. GradeBuilder not only allows the user to see what equations and coefficients are used, but allows him/her to select which algorithms to use and adjust the coefficients. The user can even write their own algorithms and select them for use with their own grade.

To build a new grade, the sample grade that is closest to the new grade can be duplicated and given a new name. Then the equations and coefficients for each microstructure process during the austenite phase, phase transformation, and final mechanical properties can be selected to best represent the microstructure characteristics of the new grade. The austenite process selection screen of the GradeBuilder is shown in Figure 27.

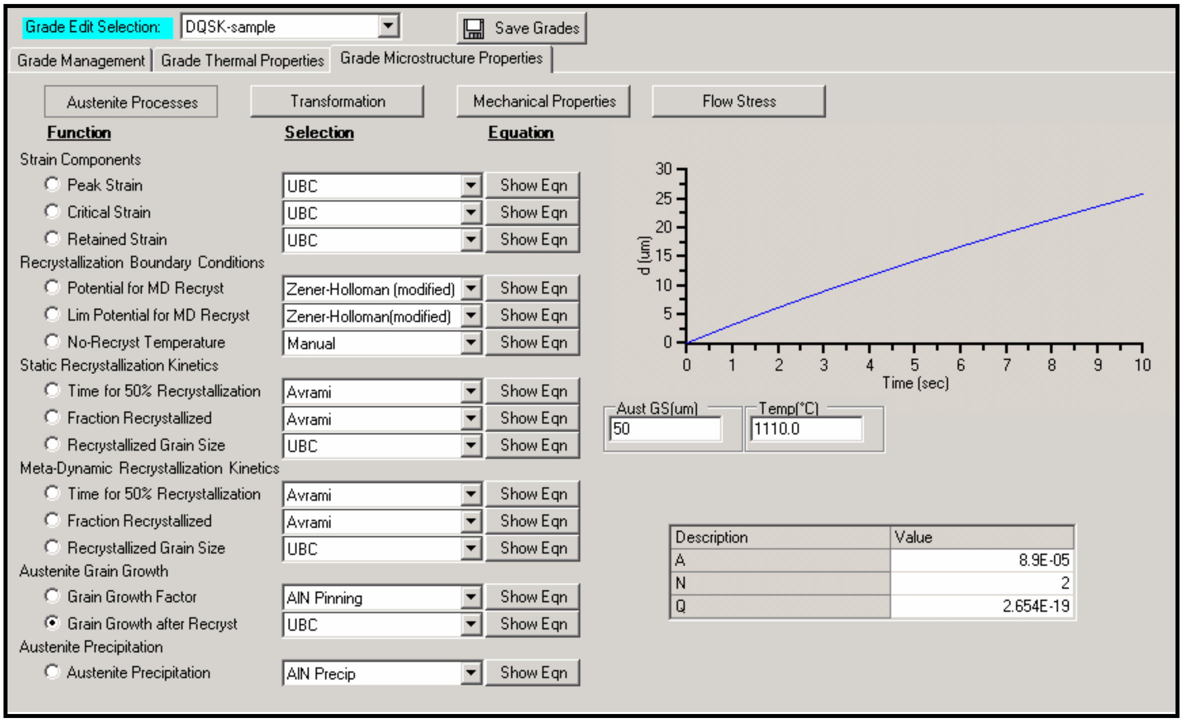


Figure 27 – GradeBuilder Screen

Within GradeBuilder, the user also has the ability to select between two different methods of determining thermal properties of the grade being built. Method 1 – (UBC) (see Figure 28) has the thermal properties split into three phases (austenite, ferrite and pearlite curves). This method will accurately calculate the thermal properties based on when phase transformation occurs.

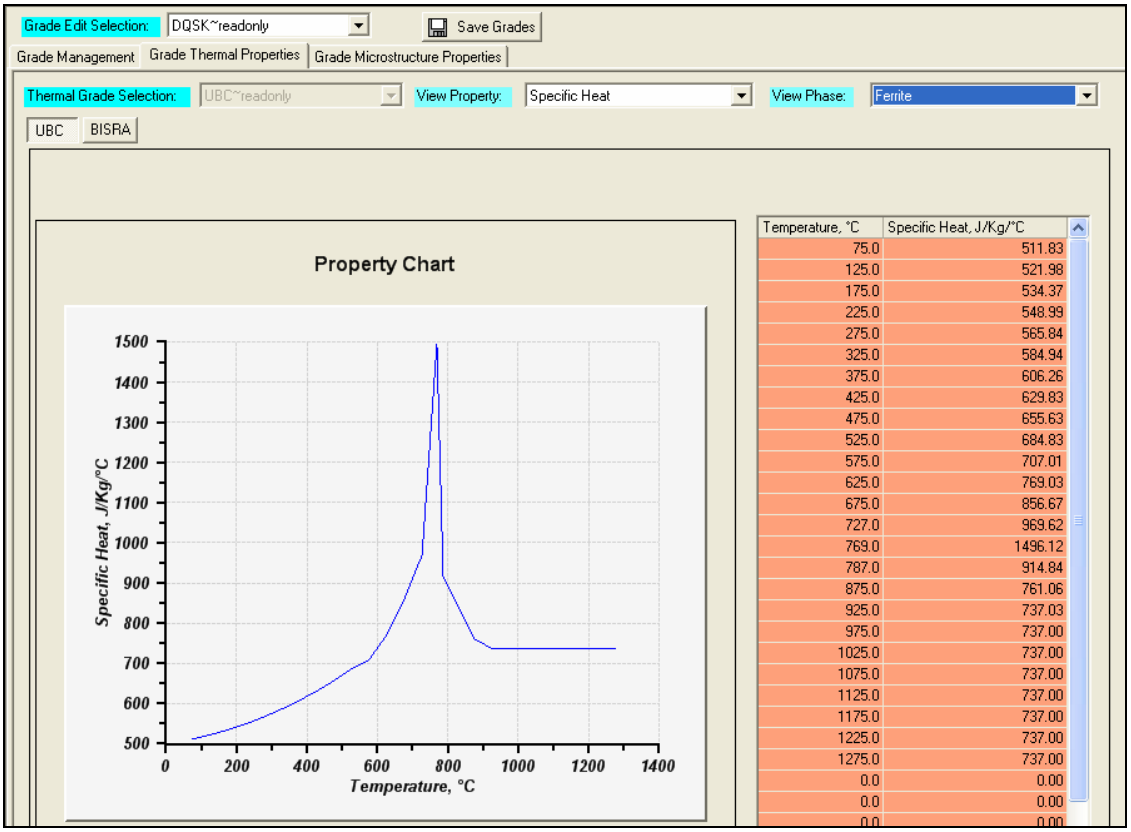


Figure 28 – Thermal Property Selection by Phase (UBC Method)

Method 2 – (BISRA) uses curves developed by the British Iron and Steel Research Association (see Figure 29). This method will describe the thermal properties based on when phase transformation occurred during development of the curves. The advantage of using these curves is that the range of the model can now be expanded to uses outside of the scope of the sample grades of steel for thermo-mechanical calculations (i.e.: stainless steel, Dual Phase, TRIP steels).

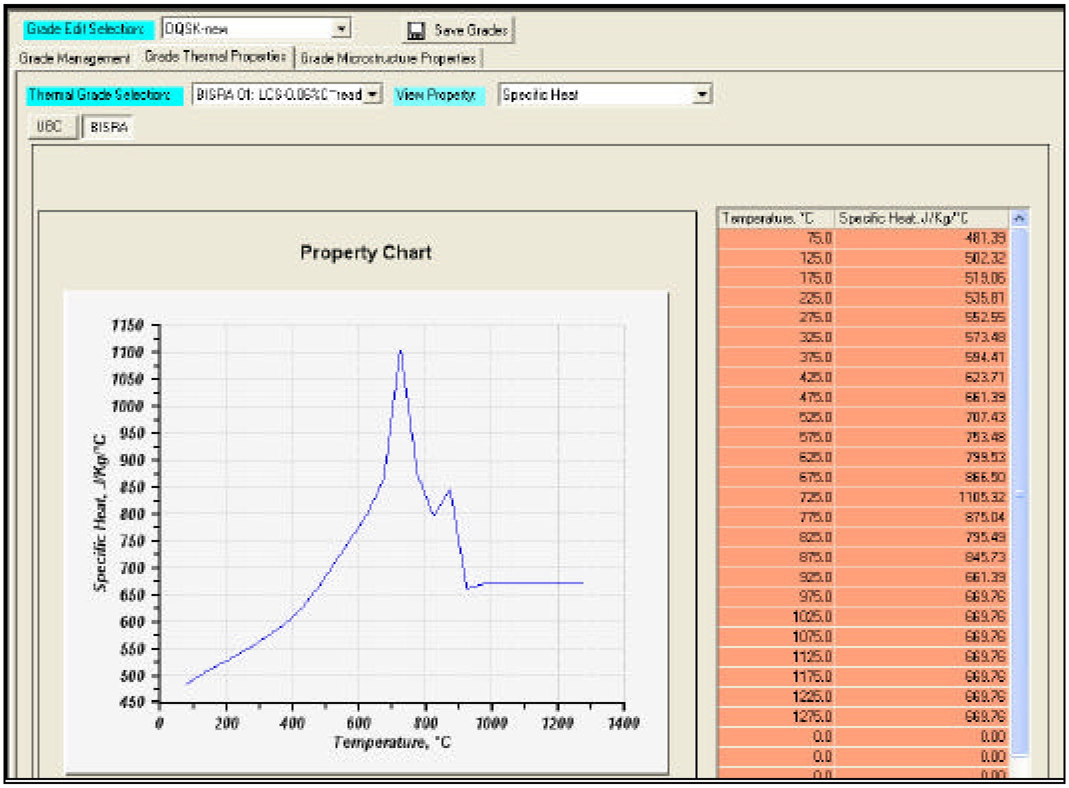


Figure 29 – BISRA Thermal Property Selection (BISRA Method)

2.4.3 Extended ROT Transformation Model into Coiler

In HSMM version 4.0, all transformation was expected to occur on the Runout Table. In cases where transformation did not fully occur, an empirical equation was employed to predict the final ferrite grain size and final ferrite fraction.

In HSMM version 6.2, this empirical equation was removed, and the transformation prediction equations used for the Runout Table are extended for use in the coiler. In this way, the correct cooling path is used to more accurately predict the transformation conditions in the coiler.

2.4.4 Improved Elongation Calculation

In the HSMM version 4.0 for the eight base grades, the elongation was calculated as a function of the tensile strength defined by two straight lines. Plant data showed that for the low tensile strength grades the elongation was being under-predicted. A power curve shown in Figure 30 was fit from plant data and introduced into version 6.2 to improve the elongation calculations, especially in the lower tensile strength range.

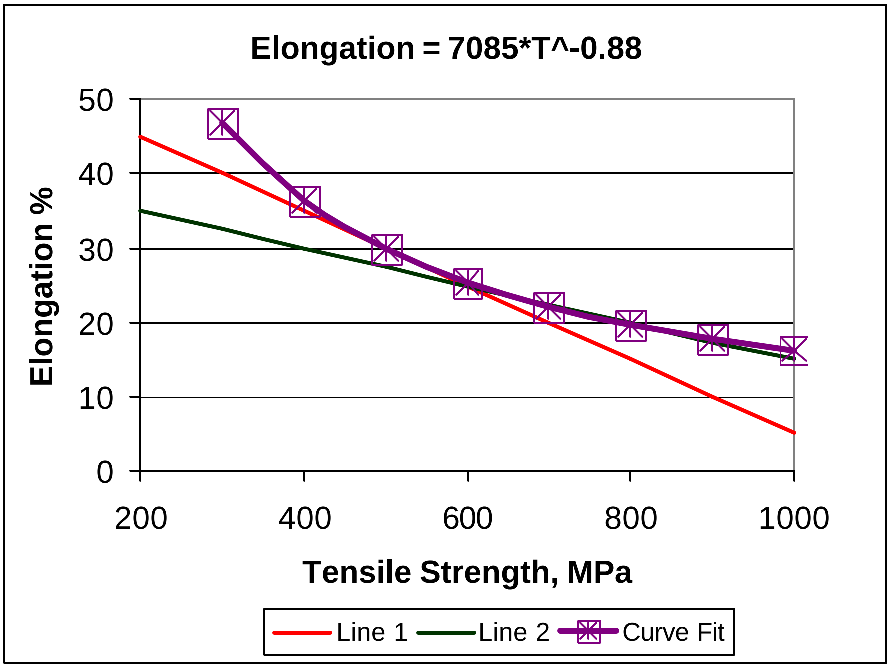


Figure 30 – New Elongation Curve

2.4.5 Improved Vanadium Precipitation Strengthening Calculation

For HSMM version 6.2, a chemistry-based Vanadium precipitation strengthening model was developed. Version 4.0 provided only a constant value for potential precipitation strengthening that was independent of the Vanadium content. After combining with Titanium, any free Nitrogen combines with Vanadium in a 4:1 ratio. The maximum strengthening that is available from precipitation is a function of the VN and excess vanadium. .

$$VNeff = Min([Nfree]*4, [V]) \qquad (2.19)$$

$$P.S. = a*VNeff + b*([V] - VNeff]) \qquad (2.20)$$

where coefficients a and b were determined

The actual amount of precipitation strengthening is a function of the Shercliff-Ashby aging curve as before. An example of the improved results is shown in Figure 31.

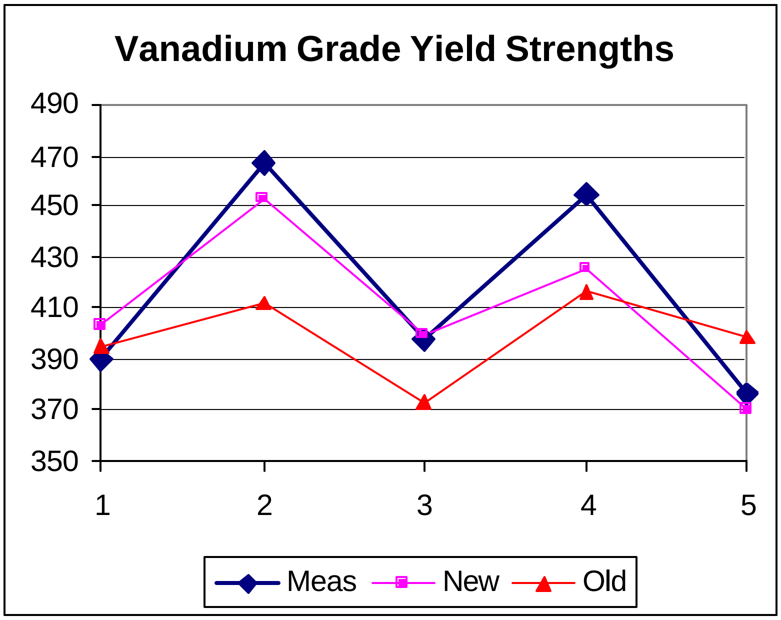


Figure 31 – Improvement in HSLA-Vanadium Grade Yield Strength Predictions

2.4.6 Added Models for Dual Phase Steel

For this enhancement, UBC was contracted to perform the necessary lab tests to develop a microstructure model for hot strip rolling of Dual Phase-Mo 600 steel. The result of this work produced the following new models for this steel:

- Ferrite Transformation Model
  - Enhanced JMAK model
  - Enhanced ferrite grain size model
- Bainite Transformation Model
- Martensite Transformation Model
- New Mechanical Properties Model

Figure 32 shows the cooling path required to produce this grade. See Appendix B for UBC report.

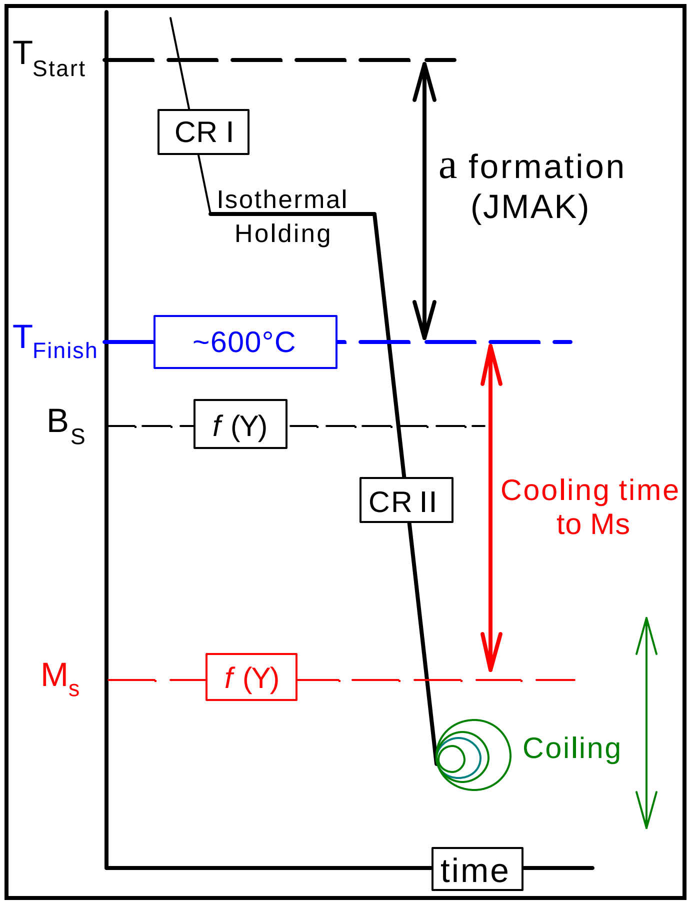


Figure 32 – Cooling Path on the Runout Table for Dual Phase Steels

3 HSMM Validation

3.1 Overview

In 2003, INTEG completed an extensive validation of the HSMM version 6.0 using a variety of grades of steel, rolled under a variety of processing conditions and from a variety of rolling mills. Four of the Enhancement Group companies providing data to validate the HSMM encompassed five rolling mills of various configurations (Table 1).

Steel Company	Mill Type	Roughing Area	Heat Retention	Finishing Area	Run Out Table	Exit Area
Dofasco	68” Hot Strip Mill	1 Reversing Stand	Heat Retention Panels	7 Stand Tandem Mill	19 Banks of Headers	3 Down Coilers
Stelco – Hamilton	148” Plate Mill	1 Reversing Stand	None	1 Stand Steckel Mill	4 Banks of Headers	1 Up Coiler & 1 Cooling Bed
Stelco – Lake Erie	2050mm Hot Strip Mill	1 Reversing Stand	Coil box	5 Stand Tandem Mill	6 Banks of Headers	2 Down Coilers
US Steel – Irvin Works	80” Hot Strip Mill	5 Continuous Stands	None	6 Stand Tandem Mill	20 Banks of Headers	2 Down Coilers
Weirton Steel	54” Hot Strip Mill	1 Rev Stand & 1 Cont. Stand	Heat Retention Panels	7 Stand Tandem Mill	18 Water Walls	2 Down Coilers

Table 1 – Mill Configurations of Supporting Steel Companies

3.2 Plant Data

The data supplied for the HSMM validation covered a variety of thicknesses, speeds, finishing temperatures, coiling temperatures, tensile strengths and amount of water used on the run out table. Some variation in the chemistry within the microstructure grade families was also introduced. The steel companies provided engineering logs, data scan files (rolling speeds, forces, temperatures, etc.) and laboratory data (yield strength, tensile strength, elongation, grain size, etc.). Data was obtained for seven of the eight HSMM microstructure grades. To further improve the accuracy of the model, the actual chemistry of each piece was used for the microstructure calculations. Table 2 displays the approximate range of processing parameters and Table 3 the range of key elements of the steels utilized.

Finished Thickness (Strip)	2mm to 9mm
Finished Thickness (Plate)	9mm to 16mm
Finishing Temperature Range	800°C to 950°C
Coiling Temperature Range	600°C to 725°C
Yield Strength Range	200MPa to 650MPa
Tensile Strength Range	300MPa to 700MPa

Table 2 – Processing Parameter Ranges

Grade		C	Mn	P	Si	Ni	Cr	Mo	Nb	Ti	V	Al	N
A36	Min												
	Max	0.160	1.36	0.011	0.250	0.011	0.030	0.002	0.002	0.002	0.002	0.037	0.007
DQSK	Min	0.025	0.26	0.009	0.011	0.021	0.051	0.006				0.025	0.004
	Max	0.064	0.40	0.020	0.030	0.100	0.100	0.020	0.002	0.008	0.008	0.050	0.010
HSLA V	Min	0.050	0.60										0.007
	Max	0.070	0.75	0.020	0.060	0.100	0.100	0.015			0.060		0.010
HSLA Nb	Min	0.050	0.55		0.100			0.020	0.010			0.020	
	Max	0.090	1.05	0.015	0.250	0.100	0.100	0.050	0.050	0.004	0.008	0.040	0.010
HSLA Nb/Ti 80	Min	0.060	1.25		0.100	0.020	0.029	0.006	0.065	0.030			0.005
	Max	0.080	1.50	0.020	0.325	0.100	0.100	0.015	0.085	0.050		0.035	0.007
IF NbRich	Min		0.05	0.005		0.040	0.060		0.008	0.045		0.020	0.003
	Max	0.005	0.20	0.020	0.030	0.100	0.100	0.030	0.025	0.065	0.019	0.055	0.006
IF NbLean	Min		0.10								0.050	0.020	
	Max	0.005	0.20	0.020	0.030	0.100	0.100	0.030	0.006	0.008	0.084	0.055	0.006

Table 3 – Chemistry Range

Data for approximately 50 coils of steel was evaluated. Since the effort covered five different rolling mills, differences in data gathering, reporting, terminology and testing were introduced. Every effort was made to be as consistent as possible for selecting comparison points between mill data and HSMM calculated data. The final analysis indicated that having the exact temperature reading or the exact force measurement or the exact whatever was not extremely important to the final mechanical property results. These measurements could include their own natural margin of error and the HSMM could still predict, with very acceptable accuracy, the tensile strength of the piece being modeled. If anything, the variation in data measurement, collection and testing provided a possible source of error that was not necessarily caused by the models, but observed when comparing actual versus predicted results.

3.3 Results

The measured parameter that deviated the most from the predicted value was the final ferrite grain size. On a percentage basis, when comparing actual versus calculated, the final ferrite grain size comparison varied from as little as a 1% error to as much as a 50% error. However, even though the final mechanical property calculations are partially grain size dependent, the results did not consistently show the same relative magnitude of error for tensile strength comparisons between actual and calculated. This can be primarily explained by the error that occurs in the "measurement" of the ferrite grain size.

Since no uniform practices were issued any to all of the supporting steel companies prior to their submission of the grain size measurements, a natural error in measurement can be expected. However, it is important to point out that the grain sizes calculated by the HSMM were indicative of the magnitude of the measured grain sizes. For example, one steel sample had a measured grain size of 7.9 microns while the model predicted a final ferrite grain size of 4.9 microns. Although this was almost a 40% error, the magnitude of the grain size prediction was in an acceptable range because the tensile strength prediction was within 1%.

The ultimate goal of the HSMM is to predict the final mechanical properties of the steel being rolled in a hot mill. Due to the variations mentioned above, it was decided that the best or most consistent and reliable parameter that could be used to measure the model's performance would be the tensile strength. The tensile strength is viewed as the best measure of performance because this test is the most repeatable in the lab and thus has the least deviation (error) built-in on the measurement side. The yield strength calculation, on the other hand, not only introduces a degree of error in the accuracy and repeatability of the test, but also introduces a variety of methods to report the results such as a Lower Yield Point, 0.2% Offset or 0.5% Under Load thus creating some potential error in comparison using data gathered from multiple steel companies.

The following charts (Figures 33, 34, 35, 36, 37) provide a summary of the comparison between the actual and calculated values for the temperature exiting the finishing mill, the coiling temperature, the yield strength, the tensile strength, and the ferrite grain size. Range lines are added to the graphs to show a range of ± 20°C for the temperatures and ± 5%MPa for the yield and tensile strengths. A fixed error range for the temperatures was used because the relative spread between the lowest and highest temperature was only about two hundred degrees. For the mechanical property charts, a percentage error range was used because the range from the lowest to the highest was about 400MPa.

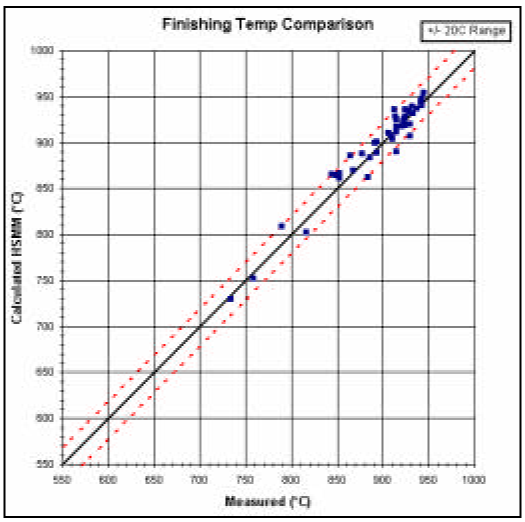


Figure 33 – Finishing Temperature Comparison

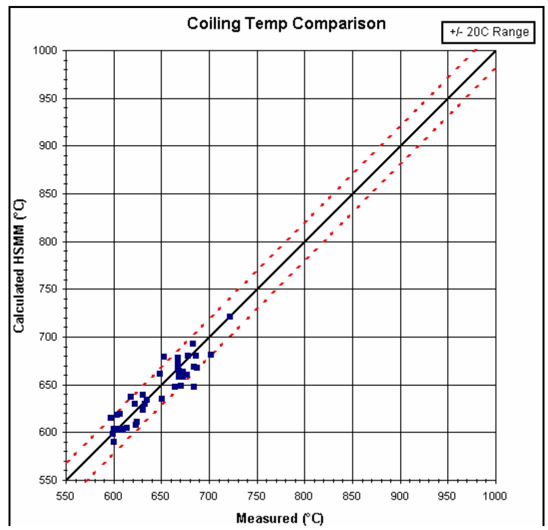


Figure 34 –Coiling Temperature Comparison

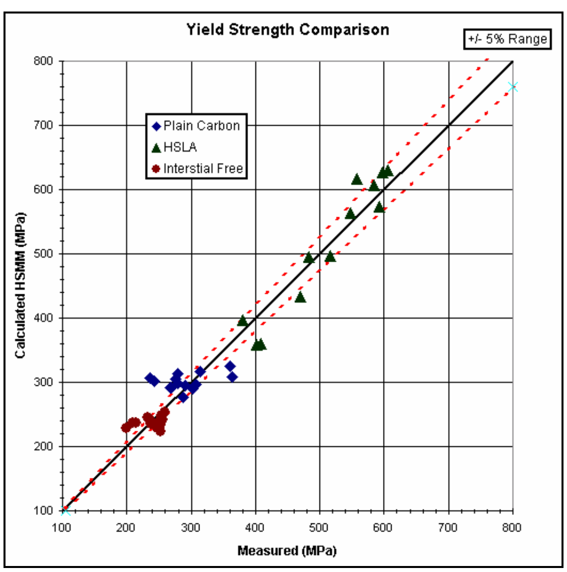


Figure 35 – Yield Strength Comparison

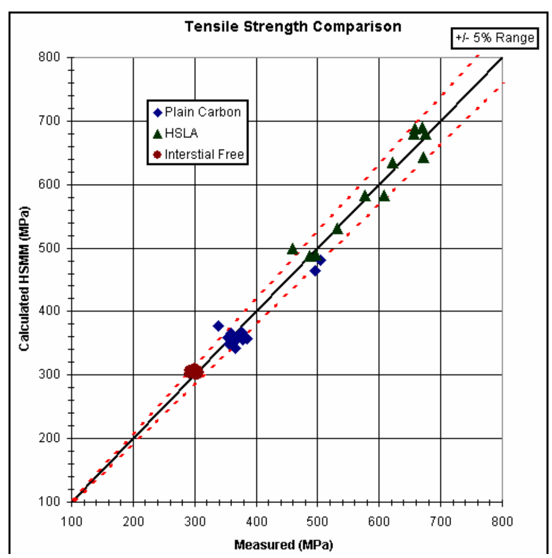


Figure 36 – Tensile Strength Comparison

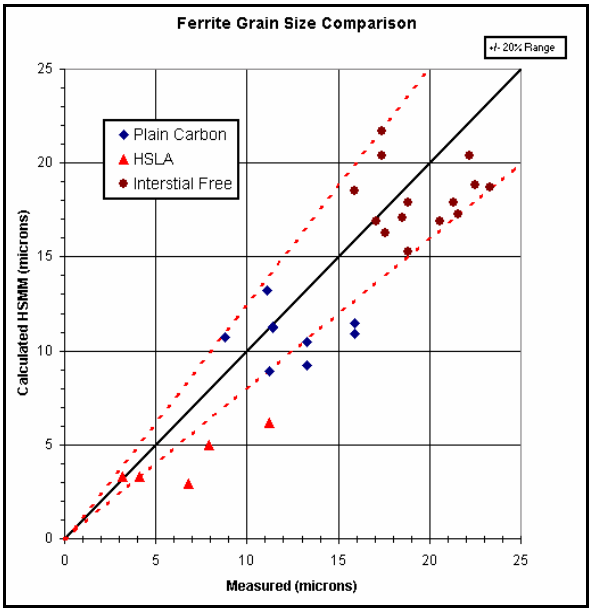


Figure 37 – Ferrite Grain Size Comparison

3.4 Validation Summary

As can be seen from the above charts and the statistical summary in Table 4, the HSMM has been validated using data from coils produced on a variety of mills and good agreement has been achieved for the variety of products and processing parameters covered. When comparing the final results for tensile strength, a very acceptable range of errors have been achieved with an average percent error (calculated from the average absolute error) of 3.03% or a ± 3% error. With this type of performance, the HSMM version 6.2 can be used for conducting a variety of off-line analyses knowing that a proper trend and/or relative prediction can be achieved.

Parameter	Avg. Absolute Error	Avg. Percentage Error
Finishing Temperature	9.14°C	1.02%
Coiling Temperature	11.21°C	1.73%
Yield Strength	23.93MPa	7.49%
Tensile Strength	13.27Mpa	3.03%
Ferrite Grain Size	2.65μm	19.67%

Table 4 – Statistical Analysis of Comparison between Actual and Calculated

4 HSMM User Documentation

A complete set of documentation including users and technical manuals were generated during the project and are included in Appendix A.

4.1 User's Manual

The purpose of this document is to provide an overview of the HSMM, a brief background on some of the theories used in the HSMM, and a thorough description of the HSMM User's Interface and its functionality.

4.2 Getting Started

This document is intended to help the user get quickly oriented with the HSMM, understand how to utilize the HSMM to study and improve his/her mill operations and to make him/her aware of some of the advanced features of the HSMM. The sections of this document are:

- Part I – Quick Tour
- Part II – Working with the HSMM

4.3 Calibration Guide

This guide provides the procedures for properly setting up an HSMM Calibration Module to accurately simulate a particular grade. These procedures involve using plant data for tuning the temperature and force model coefficients to get the calculated values to closely match the measured ones for both the single and multiple node models.

4.4 Client Database Link Instructions

This document contains general information and instructions on how to connect the HSMM interface to a plant database for importing data into new rolling schedules.

4.5 Microstructure Guide

The purpose of this document is to provide an understanding of the underlying methodologies used for microstructure modeling in the HSMM, and how the user can best apply this model to his/her grades of steel using the GradeBuilder Module.

4.6 Technical Manual

The document describes the thermo-mechanical calculations that are performed in the HSMM and how they are applied in simulating a work piece rolling through an entire hot strip mill. The equations and numerical methods that are used in these calculations are also provided.

5 Conclusion

With the release of version 6.2, the validation and enhancement goals of this project were successfully achieved in January, 2005. At that time the HSMM had already been purchased by three steel producing companies located on three different continents. They and the supporting steel companies continue to find outstanding value in the HSMM as a beneficial tool in saving them time and money for a variety of practical applications.

Appendix A – HSMM User Documentation

The HSMM User Documentation as described in Section 4 is provided in the following files in PDF format:

- User Manual.doc
- Getting Started.doc
- Calibration Guide.doc
- Client Database Link Instructions.doc
- Microstructure Guide.doc
- Technical Manual.doc
- Flow Stress Grade Development Procedure.doc
- Microstructure Grade Development Procedure.doc

Appendix B – UBC Report on Dual Phase-Mo 600 Steel

The UBC report titled "Microstructure model for hot strip rolling of DP-Mo steel" referred to in Section 2.4.6 is provided in the following PDF file:

- UBC-ReportforInteg_Nov2004Mechanical Properties.doc
- UBC-ReportforInteg_Nov2004microstructure.doc

<u>Protected Metals Initiative Data</u>

This Protected Metals Initiative Data was produced under a Cooperative Agreement identified as DE-FC36-97ID13554 under a DOE Metals Initiative Project and may not be published, disseminated or disclosed to others until five (5) years from March 30, 2005 unless written authorization is obtained from the American Iron and Steel Institute, Vice President of Manufacturing and Technology. Upon expiration of the period of protection set forth in this legend, the Government shall have unlimited rights in this data.